FINAL REPORT

LCEM@UNSW

COMPOSITES: CALCULATING THEIR EMBODIED ENERGY

Prepared by: S. Kara and S. Manmek

Life Cycle Engineering & Management Research Group @ The University of New South Wales

2009

PREFACE

The 'Composites: Calculating Their Embodied Energy Study' is a multi-partner collaboration project, led by the Department of Employment, Economic Development and Innovation (DEEDI), the State of Queensland. The main objectives of the project are to:

- Calculate the embodied energy of six fibre composite materials using the cradle-to-gate analysis;
- Calculate the embodied energy of the whole life cycle for the six composite products and their comparable products that are made from traditional materials using the cradle-to-grave analysis;
- Generate a spreadsheet based model to estimate the energy usage and greenhouse emissions from all the processes within the system boundaries of the analyses;
- Life Cycle Assessment for the composite products.

This project will fulfil several obligations in the Fibre Composites Action Plan. These include:

- Analysing the impact of this technology has on the environment compared with 'traditional' materials including steel, concrete and aluminium; and
- Establishing ongoing dialogue with emerging markets/industries to raise the profile of fibre composites and encourage fibre composites uptake.

Other outcomes for the department include the ability to provide:

– Export-focussed companies with a technical manual which clearly states the impact on the environment of their product contains. (This is becoming more important to companies exporting to environmentally sensitive regions including the European Union and Japan); and

– Companies tendering for infrastructure-related projects in industries like mining, building and construction with technical data on the advantages of their fibre composite products have over products manufactured from traditional materials such as concrete, steel, aluminium and hardwoods.

EXECUTIVE SUMMARY

Background

The fibre composites industry is one of the growing industry sectors in Australia. The manufacturing of composite products like glass or carbon fibre reinforced plastics continues to expand due to the increasing demand of these products in various industries including aircraft, automotive, construction and marine. With their strength, high durability, high strength-to-weight ratio and cost effectiveness, composite products have replaced the use of traditional materials such as stainless steel and aluminium in many applications.

In April 2006, the Honourable Anna Bligh MP, then Deputy Premier, Treasurer, and Minister for State Development, Trade and Innovation launched the Queensland Government's Fibre Composites Action Plan. The purpose of the Action Plan was to build on existing research and manufacturing strengths and take advantage of opportunities presented by this dynamic enabling technology.

It introduced over 50 initiatives developed in collaboration with industry to drive growth in Queensland fibre composites, increase critical mass and focus on global competitive advantages. Programs fall into theme areas ranging from skills formation to research and product development, commercialisation, identification of new markets and manufacturing process improvement.

Purpose

The 'Composites: Calculating their Embodied Study' project aimed to quantify the life cycle embodied energy of composite products manufactured in Australia and their comparable products manufactured using other traditional materials. It took into account raw materials manufactured in Australia as well as those imported from overseas. The finished composite products manufactured overseas and then imported to Australia were not part of this project.

Objectives and Scopes

The main objective is to analyse the embodied energy of the cradle-to-factory and cradle-to-grave. The cradle-to-factory is the analysis for making 1 kilogram of the glass or carbon fibre reinforced plastics which comprises of the raw material including the energy extraction and the transportation from suppliers to the composite manufacturers. The cradle-to-grave analysis is the calculation from the total amount of the composite materials required to make a composite product down to the manufacturing processes; the usage i.e. the installation and maintenance activities; and the End-of-life (EOL) life cycle stages that covers the waste collection transportation and the disposal processes.

Embodied energy of the composite products included in the analyses were limited to those incurred during the extraction of raw materials, transportation from suppliers to composites manufacturers, manufacturing process, installation, operation, maintenance, transportation from a customer to a disposal site and a disposal process. The analyses were conducted for a particular unit of products namely a square metre of roof tile, a square metre of roof sheet, a powerboat hull, a linear metre of an I-Beam, 2.5 metres of a power-pole cross-arm and an aircraft hinge fitting. The embodied energy of the composite products are compared to traditional products which are made from concrete, galvanised steel, aluminium, stainless steel (316), hardwood timber and titanium respectively.

Approach

The cradle-to-factory and the cradle-to-grave analyses were the main approach in analysing the embodied energy of the fibre composite products. The cradle-to-factory analysis in this study assessed the embodied energy in making one kilogram of six different fibre composite materials namely five glass reinforced plastics and one type of carbon fibre reinforced plastics which are used to make the fibre composite products. This analysis included two main embodied energy sources as shown in the left section of Figure E.1. They were the extraction energy of raw materials and the transportation of the raw materials from the materials suppliers to the composites manufacturing companies.

Subsequently, the cradle-to-grave analysis circumscribed the embodied energy of the entire life cycle for both the composite and the traditional products as shown in the right section of Figure E.1. The life cycle stages of a product include the raw materials, manufacturing process and usage to the end-of-life. The raw material stage is analysed by obtaining the cradle-to-factory results. The usage stage comprises of the installation, operation and maintenance activities and the associated transportation. The end-of-life stage considers the transportation of the waste collection and the disposal process.

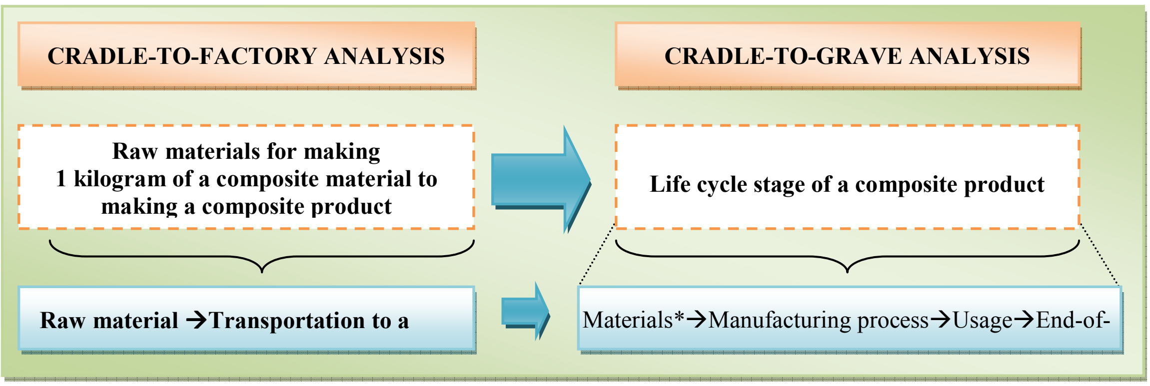


Figure E.1: Two main embodied energy sources of the cradle-to-factory analysis.

The input data for this study was provided primarily by six composites manufacturers. When the required input data was unavailable, assumptions were made with reference to the collected data from the literature review and the available databases from the Life Cycle Assessment software, SimaPro 7.1.8 software.

Embodied Energy Calculation Tool

The embodied energy of the cradle-to-factory and the cradle-to-grave analyses was calculated using three Life Cycle Impact Assessment (LCIA) methods in order to provide a detailed embodied energy results. The selected LCIA methods were the Cumulative Energy Demand version 1.04 (CED1.04), the IPCC GWP 100a version 1.00 (IPCC1.00) and the Eco-Indicator 99 H/A version 2.03 (EI992.03) methods from the Life Cycle Assessment software, SimaPro 7.1.8. These methods assess and generate the embodied energy results in terms of the primary energy consumption in a unit of MJ_{eq} (Mega joule equivalent), the greenhouse gas emissions in a unit of kilogram of carbon dioxide equivalent (kg CO_{2eq}) and also the total environmental impacts in a unit of single score points (points).

Mega Joules (MJ) and a kg CO_{2eq} are the common units of embodied energy values which present the primary energy consumption or the emitted greenhouse gas during the product life cycle. Whilst, the single score points results were additionally given as a full Life Cycle Assessment result which assesses the actual environmental impacts namely human health, the ecosystem quality and resource use.

In practice, these three embodied energy results can be employed independently in different situations as they represent three distinctive environmental aspects. The MJeq results focus on the primary energy consumption which can be used as a guideline for a quick and a simple analysis of the total energy used in making a product. The kg CO_{2eq} results represent the well-known greenhouse gas emissions such as CO_2 emission. This result can be easily used to communicate with the public. Ultimately, the single score points results denote the actual environmental impacts which are a detailed Life Cycle Assessment analysis. Such results may be employed in assessing the genuine environmental performance of products or any improvement of different product designs.

Main conclusions

Cradle-to-factory analysis

Figures E.2 to E.4 summarise the detailed embodied energy results for cradle-to-factory results which are two embodied energy results namely the primary energy consumption and the greenhouse gas emissions as well as the total environmental impacts result. Therefore, these results are expressed in a unit of MJ_{eq} per kg, kg CO_{2eq} per kg and points per kg respectively.

The left charts of Figures E.2 to E.4 present the three results of the five glass-reinforced plastics from five composite manufacturers, namely B-Pods Pty Ltd (B-Pod), Ampelite Fibreglass Pty Ltd

(Ampelite), Mustang Marine Australia Pty Ltd (Mustang), Exel Composites (Exel) and Wagners Composite Fibre Technologies Manufacturing Pty Ltd (Wagners). The right charts of these figures show the three embodied energy results for the carbon fibre reinforced plastic from Boeing Research & Technology Australia (Boeing). Each chart displays the cradle-to-factory results in terms of the two main embodied energy sources which are the raw material extraction and the transportation of the raw materials from suppliers to the composites companies. The last bar of all charts in Figures E.2 to E.4 gives the total results of which are the sum of the raw material extraction and the transportation of the raw materials.

According to these figures, the fluctuation of the cradle-to-factory results are found in the fibre composites whereby the total results for the carbon fibre reinforced plastic are 315 MJ_{eq}/kg, 10 kg CO_{2eq}/kg and 1.2 points/kg. The reasons being that these materials were analysed based on the provided input data from the corresponding manufacturers with varying level of detail. Each material contains different combinations of fibreglass, resin and 'other' materials that were transported by a variety of transportation types and travel distance as they were exported from a diverse range of locations in overseas.

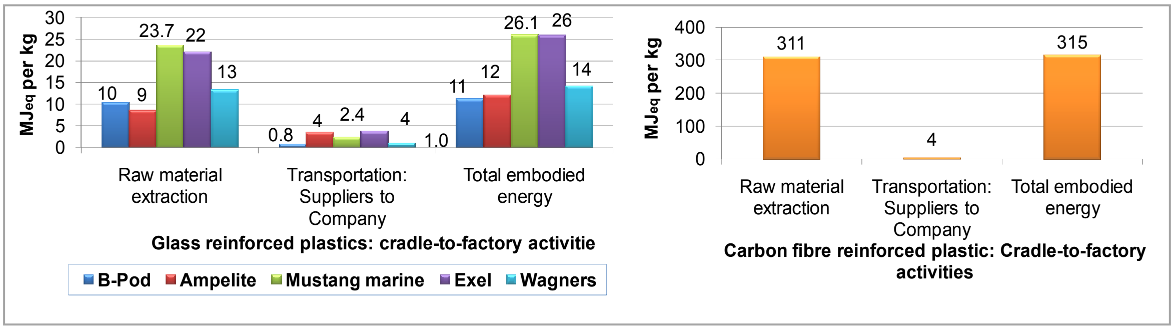


Figure E.2: Primary energy consumption results of the cradle-to-factory analysis in MJ_{eq} per kg.

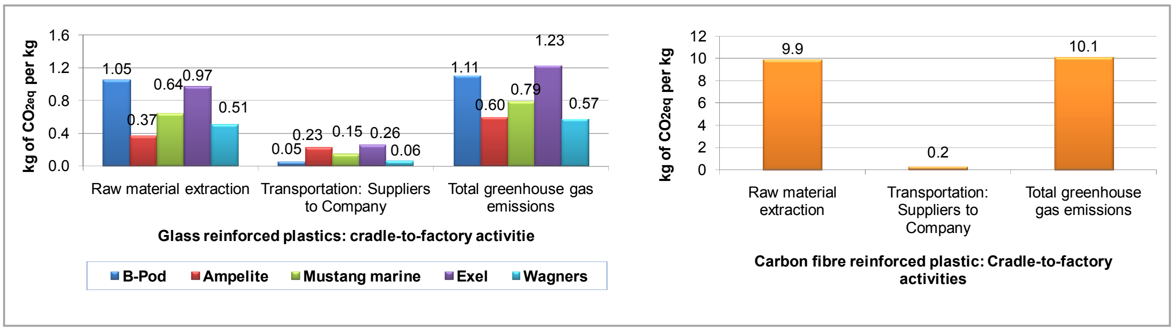


Figure E.3: Greenhouse gas emissions results of the cradle-to-factory analysis in kg CO_{2eq} per kg.

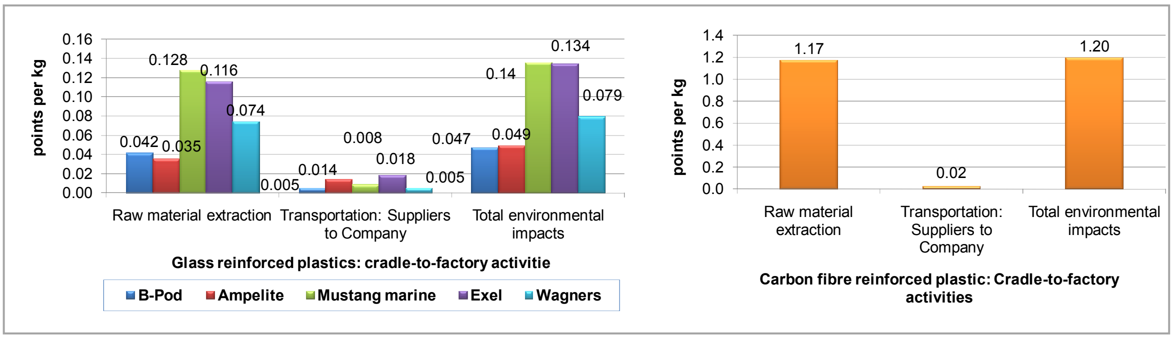


Figure E.4: Total environmental impacts results of the cradle-to-factory analysis in points per kg.

The distinct contributions of the two embodied energy sources are clearly revealed. The finding suggests that the embodied energy of the glass or carbon reinforced plastics can be reduced in two different directions. The first direction is to reduce the high embodied energy of the raw material extraction using alternative raw materials with low embodied energy. The second direction is to be selective in choosing the suppliers in order to ensure low embodied energy in their delivery transportation.

Key findings: Cradle-to-factory analysis

- The embodied energy of the cradle-to-factory analysis for the six fibre composite materials in this project is comprised of the extraction energy process and the transportation from suppliers to the manufacturers. The cradle-to-factory results as shown in Figures E.2 to E.4 reveal that the predominant contributor to the embodied energy of the fibre composites came from the energy required during the extraction process.
- The extraction energy of the raw materials for the fibre composite materials in Figures E.2 to E.4 is influenced mainly by the quantities and the types of resins used. In this case, it is based on the databases from the Life Cycle Assessment software, where 1 kilogram of fibreglass has lower extraction energy than 1 kilogram of resin, whilst 1 kilogram of carbon fibre has the highest extraction energy.
- The higher contributions of the transportation in Figures E.2 to E.4 were caused by a number of factors. Road transportation was found to be the main contributing factor as it utilised higher amounts of non-renewable fossil fuel such as crude oil to transport the raw material freight over a long distance. Shipment of raw materials from overseas can also increase the embodied energy of the composite materials. Interestingly, it was found that the accumulation of the shipment of several raw materials from various overseas suppliers can further increase the embodied energy of the transportation. For instance, suppliers that were found in this study came from various locations in the Asia, Europe and US regions.

- For this project a hot spot was identified as the raw materials and/or suppliers which have a high contribution to the embodied energy results of the composite products. The hot spots analysis was conducted to make further suggestions in order to minimise or eliminate the environmental impact associated with raw materials and/or suppliers. As a result, the raw materials and suppliers which predominantly contributed to the cradle-to-factory were identified. Therefore, the suggestions to reduce these hot spots were made such as avoiding the utilisation of the road transportation for a long distance and also encouraging the manufacturers to use rail and/or water transportation. Moreover, selecting local suppliers was also suggested rather than those from overseas.

Cradle-to-grave analysis

As in the cradle-to-grave analysis, the Life Cycle Assessment method was used to assess the embodied energy of the whole life cycle of six composite products which are made from glass or carbon fibre reinforced plastics. These results were then compared with products that made of traditional materials which are aluminium, concrete, galvanised steel, stainless steel, hardwood timber and titanium.

As a result, case studies on the following fibre composite products were completed, with the detailed embodied energy results including the full Life Cycle Assessment results as given in chapters 3 to 8 of this report:

- Glass reinforced products
  - 1 square metre of roof tile made of glass reinforced plastic from B-Pods (Tractile) Pty Ltd, concrete tiles coated steel sheeting
  - 1 square metre of roof sheet made of glass reinforced plastics from Ampelite Fibreglass Pty Ltd and galvanised steel sheeting
  - A powerboat hull made of glass reinforced plastic of Mustang Marine Australia Pty Ltd and cold-formed aluminium
  - 1 linear metre of I-Beam made of glass reinforced plastic of Exel Composites and stainless steel (316)
  - 2.5 linear metre power-pole cross-arm manufactured from glass reinforced plastic of Wagners Composite Fibre Technologies (CTF) Manufacturing Pty Ltd and sawn hardwood timber
- Carbon fibre reinforced product
  - An aircraft hinge fitting manufactured from carbon fibre reinforced plastic of Boeing Research and Technology and titanium.

The Life Cycle Assessment generated the detailed embodied energy results and the full Life Cycle Assessment result using the Cumulative energy demand version 1.04 (CED1.04), the IPCC GWP 100a version 1.00 (IPCC1.00) and the Eco-Indicator 99 H/A version 2.03 (EI992.03) methods. These three results measure the primary energy consumption, the greenhouse gas emissions and the total environmental impacts. The results are expressed in terms of applications such as a unit of MJ_{eq} per square metre, kg CO_{2eq} per square metre and points per square metre respectively. The embodied energy results from the cradle-to-grave analysis are summarised in Figures E.5 to E.10.

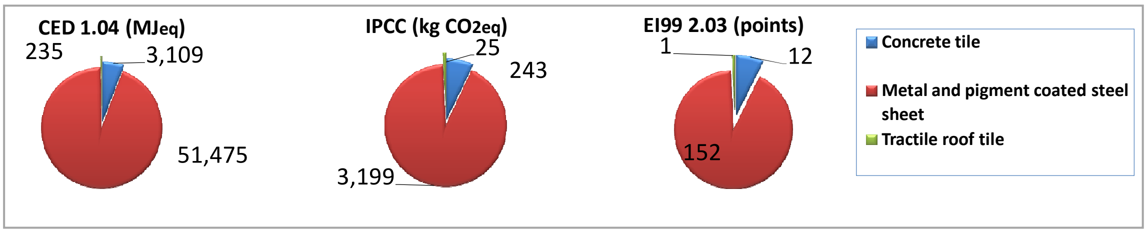


Figure E.5: Comparison of 1 square metre of roof tile manufactured from glass reinforced plastic of B-Pods (Tractile) Pty Ltd, concrete tile and coated steel sheeting.

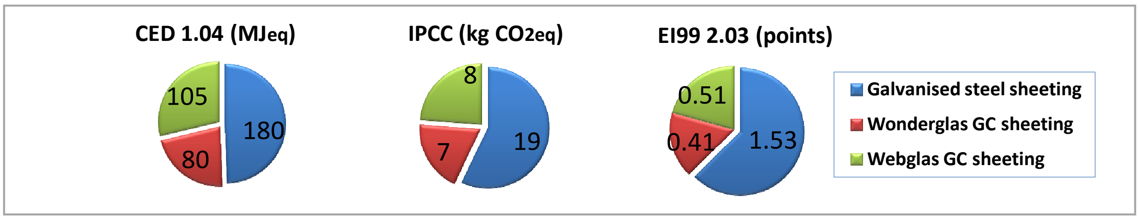


Figure E.6: Comparison of 1 square metre of roof sheet manufactured from glass reinforced plastic, namely Wonderglas GC and Webglas GC from Ampelite Fibreglass Pty Ltd as well as galvanised steel sheeting.

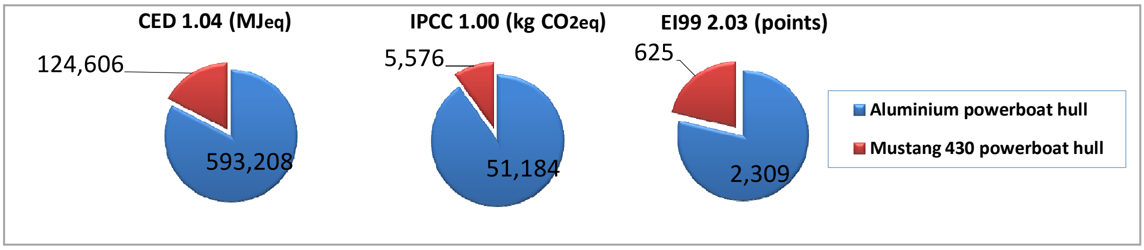


Figure E.7: Comparison of a powerboat hull manufactured from glass reinforced plastic of Mustang Marine Australia Pty Ltd and aluminium (5086).

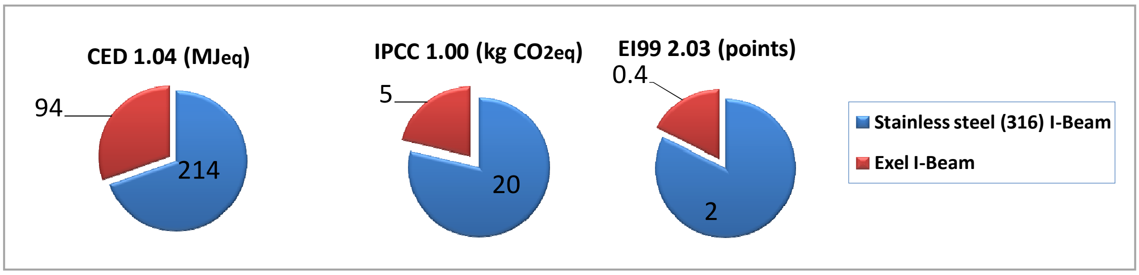


Figure E.8: Comparison of a 1 linear metre I-Beam manufactured from glass reinforced plastic of Exel composites and stainless steel (316).

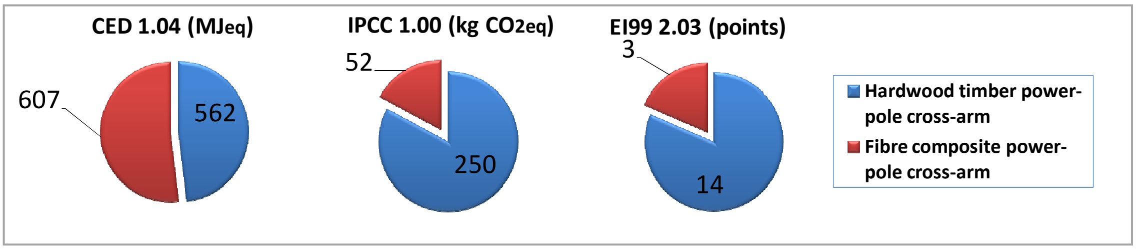


Figure E.9: Comparison of a 2.5 linear metre power-pole cross-arm manufactured from glass reinforced plastic of Wagners CTF Manufacturing Pty Ltd and hardwood timber.

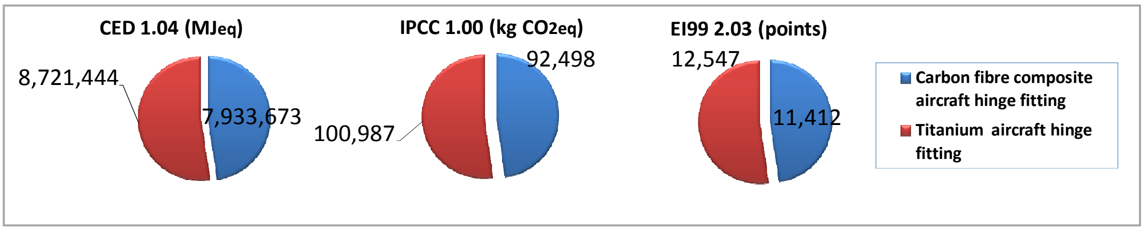


Figure E.10: Comparison of an aircraft hinge fitting manufactured from carbon fibre reinforced plastic of Boeing Research and Technology and titanium.

Key findings: Cradle-to-grave analysis

In general, the life cycle of the composite products have significantly lower embodied energy than the traditional products. The embodied energy of each life cycle stage of the composite products is given as follows:

- *Material stage:* Composite products have significantly lower embodied energy during their material stage than the traditional product. This is large due to the traditional materials require a relatively high amount of energy during their extraction process.
- *Manufacturing process (process):* Most of the composite products have higher embodied energy than the traditional products during the manufacturing process stage.
- *Usage stage:* Composite products perform significantly better than the traditional products at the usage stage. This is owing to their light-weight and corrosive resistance properties. For instance, the fuel consumption can be saved up to 35% from maintenance activities.
- *End-of-Life stage:* Despite many advantages, composite products have the shortcoming at the end-of-life stage where the composite products are currently 100% landfill but the traditional product such as steel and aluminium is 65 to 70% recyclable.

As a conclusion, based on the defined scopes and assumptions of this analysis, it was found that composite products are estimated to perform better than the traditional products in terms of their embodied energy that incurred during their life cycle stages. At the material stage, they perform the best. Their outstanding material properties such as strength and lightness are genuinely an advantage over the traditional materials in this modern era.

Recommendations

- The detailed input data should be investigated further in order to increase the accuracy of the cradle-to-factory and the cradle-to-grave analyses. For instance, some of the raw materials and suppliers were excluded from the cradle-to-factory analysis due to the limited data available from the participant companies.
- With limited resources, more participants should be involved in the project to provide input data for more case studies or to support the detailed information for such areas as extended suppliers. This will enhance the cradle-to-factory analysis where all the transportation systems are included such as those used overseas.
- For future work, the supply chain network optimisation can be further analysed to improve the hot spots as found in the cradle-to-factory results. A hot spot is defined as the raw materials and/or suppliers which have the highest contribution to the embodied energy results. Therefore, the identified raw materials and/or suppliers can be minimised or eliminated using sensitivity analysis to test the implementation in a practical environment.
- The energy efficiency during the manufacturing, installation, usage and maintenance processes can be further investigated to improve their environmental performance. This can be achieved by measuring or monitoring the energy consumption during the operation of these activities. Subsequently, the Life Cycle Assessment can be performed to improve their performance.
- Improving the recyclability of composite products can be a future challenge for the composites industry. This will not only help in improving the embodied energy efficiency of the composite products but also their competitiveness in the international market. As the recycling rate is one of the main requirements in the exportation of products to overseas markets such as Europe and Japan.
- This investigation should be accompanied by a Life Cycle Costing analysis in order to understand the true cost of composite products in a cradle-to-grave scenario. This is necessary in order to completely assess the sustainability of component products, which will lead to a win-win situation where the environment is protected and the economy sustained.

TABLE OF CONTENTS

PREFACE **2**

EXECUTIVE SUMMARY **3**

Background 3

Main conclusions 5

Recommendations 11

TABLE OF CONTENTS **12**

TERMS AND ABBREVIATIONS **17**

CHAPTER 1 PROJECT OVERVIEW **18**

1.1 Introduction 18

1.2 System boundary of the cradle-to-factory analysis 20

1.2.1 Objectives 20

1.2.2 Scopes 20

1.2.3 Input data assumptions 21

1.3 System boundary of the cradle-to-grave analysis 22

1.3.1 Objectives 22

1.3.2 Scopes and limitations 22

1.3.3 Input data assumptions 24

1.4 The embodied energy methodology and expected outcome 25

1.5 Report outline 27

1.6 Conclusion 29

CHAPTER 2 EMBODIED ENERGY ANALYSIS **30**

2.1 Introduction 30

2.2 Life Cycle Assessment 30

2.3 Embodied Energy Analysis 34

2.4 Methodology Overview 35

2.5 Data Sources Summary 38

2.5.1 Data quality and uncertainty 42

2.6 Input-Output Model 44

2.7 Conclusion 47

CHAPTER3 B-PODS PTY LTD (TRACTILE) -EMBODIED ENERGY OF ROOF TILE.....48

3.1 Introduction 48

3.2 Methodology Overview 51

3.2.1 Embodied energy analysis 51

3.2.2 Scopes and assumptions of the embodied energy analysis 52

3.3 Material and Product description 56

3.3.1 Fibre composite description 56

3.3.2 A roof tile description 57

3.4 Input Data 58

3.5 Embodied Energy Results 60

3.5.1 Cradle-to-factory Results and Discussion 60

3.5.2 Cradle-to-grave Results and Discussion 64

3.6 Conclusion 73

CHAPTER 4 AMPELITE FIBREGLASS PTY LTD -EMBODIED ENERGY OF ROOF SHEETING...75

4.1 Introduction 75

4.2 Methodology Overview 77

4.2.1 Embodied energy analysis 77

4.2.2 Scopes and assumptions of the embodied energy analysis 78

4.3 Material and Product description 83

4.3.1 Fibre composite description 83

4.3.2 A square metre roof sheeting description 84

4.4 Input Data....85

4.5 Embodied Energy Results....87

4.5.1 Cradle-to-factory results and discussion....87

4.5.2 cradle-to-grave results and discussion....91

4.6 Conclusion....97

CHAPTER 5 MUSTANG MARINE AUSTRALIA PTY LTD – EMBODIED ENERGY OF POWERBOAT HULL....99

5.1 Introduction....99

5.2 Methodology Overview....102

5.2.1 Embodied energy analysis....102

5.2.2 Scopes and assumptions of the embodied energy analysis....103

5.3 Material and Product description....107

5.3.1 Mould fibreglass description....107

5.3.2 A powerboat hull description....109

5.4 Input Data....109

5.5 Embodied Energy Results....111

5.5.1 Cradle-to-factory Results and Discussion....111

5.5.2 Cradle-to-grave Results and Discussion....115

5.6 Conclusion....120

CHAPTER 6 EXEL COMPOSITES – EMBODIED ENERGY OF I-BEAM....122

6.1 Introduction....122

6.2 Methodology Overview....124

6.2.1 Embodied energy analysis....124

6.2.2 Scopes and assumptions of the embodied energy analysis....126

6.3 Material and Product description....130

6.3.1 Pultruded fibre composite description....130

6.3.2 A linear metre I-Beam description....131

6.4 Input Data..133

6.5 Embodied Energy Results..134

6.5.1 Cradle-to-factory Results and Discussion..134

6.5.2 Cradle-to-grave results and discussion..138

6.6 Conclusion..143

CHAPTER 7 WAGNERS CFT MANUFACTURING PTY LTD – EMBODIED ENERGY OF POWER-POLE CROSS-ARM..145

7.1 Introduction..145

7.2 Methodology Overview..147

7.2.1 Embodied energy analysis..147

7.2.2 Scopes and assumptions of the embodied energy analysis..148

7.3 Material and Product description..153

7.3.1 Fibre composite description..153

7.3.2 A power-pole cross-arm description..154

7.4 Input Data..154

7.5 Embodied Energy Results..156

7.5.1 Cradle-to-factory results and discussion..156

7.5.2 Cradle-to-grave Results and Discussion..160

7.6 Conclusion..165

CHAPTER 8 BOEING RESEARCH AND TECHNOLOGY AUSTRALIA– EMBODIED ENERGY OF AIRCRAFT HINGE FITTING:..167

8.1 Introduction..167

8.2 Methodology Overview..169

8.2.1 Embodied energy analysis..169

8.2.2 Scopes and assumptions of the embodied energy analysis..170

8.3 Material and Product description..175

8.3.1 Carbon fibre composite description..175

8.3.2 An aircraft hinge fitting description..176

8.4 Input Data....176
8.5 Embodied Energy Results....178
8.5.1 Cradle-to-factory results and discussion....178
8.5.2 Cradle-to-grave Results and Discussion....181
8.6 Conclusion....186

CHAPTER 9 CONCLUSION....188

CHAPTER 10 RECOMMENDATIONS....191

ACKNOWLEDGEMENTS....194

APPENDIX A TABLES OF AIR POLLUTANTS RESULTS....195

APPENDIX B TECHNICAL MANUAL: MATERIAL AND ENERGY FLOW SPREADSHEET MODEL....198

Introduction....198
Model worksheet....198
Summary of CTF results worksheet:....201
Summary of CTG results worksheet:....201

APPENDIX C: GENERAL DATABASE BACKGROUND OF THE EMBODIED ENERGY ANALYSIS....203

Fibre....203
Resin....207
Chemicals....209
Transportation....215
Electricity....218
Disposal process....220

TERMS AND ABBREVIATIONS

Abbreviation	**Meaning**
CED1.04	Cumulative Energy Demand version 1.04 method
CO	Carbon monoxide
CO_2	Carbon dioxide
DEEDI	Department of Employment, Economic Development and Innovation
EI992.03	Eco-Indicator 99 H/A version 2.03 method
EOL	End-of-Life
GWP	Global Warming Potential
IPCC1.00	IPCC 2007 GWP 100a version 1.00 method
kg CO_{2eq}	Kilogram of carbon dioxide equivalent
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCEM	Life Cycle Engineering & Management Research Group @ UNSW
MJ	Mega joule
MJ_{eq}	Mega joule equivalent
MSDs	Material Safety Datasheets
NO_2	Nitrogen dioxide
Pts	Points
SO_2	Sulphur dioxide
SQM	Square metre
STDEV	Standard deviation
VOC	Volatile Organic Compound

CHAPTER 1

PROJECT OVERVIEW

1.1 Introduction

Many manufacturers for cars, aircraft, ships and construction materials generally use composite materials such as fibreglass or carbon fibre reinforced plastics in their products. This is because of their outstanding material properties, including high strength-to-weight ratio, high durability, strong strength, corrosion resistance and cost effectiveness.

In April 2006, the Honourable Anna Bligh MP, then Deputy Premier, Treasurer, and Minister for State Development, Trade and Innovation launched the Queensland Government's Fibre Composites Action Plan. The purpose of the Action Plan was to build on existing research and manufacturing strengths and take advantage of opportunities presented by this dynamic enabling technology.

This action plan has introduced over 50 initiatives in collaboration with industry to drive growth in Queensland fibre composites industry, increase critical mass and focus on global competitive advantages. Programs fall into theme areas ranging from skills formation to research and product development, commercialisation, identification of new markets and manufacturing process improvement.

The Department of Employment, Economic Development and Innovation (DEEDI), the State of Queensland, established the 'Composites: Calculating Their Embodied Energy Study' project to investigate the embodied energy for the life cycle of composite products.

The main aim of this project was to assess the embodied energy of the composites materials and composite products in order to support the growth of the composites industry in Queensland. The 'Composites: Calculating their Embodied Study' project aimed to quantify the embodied energy contained in fibre composite products compared to products manufactured using other materials. The embodied energy sources include the primary energy consumption of material extraction, manufacturing processes, transportation incurred during the production of a product. This project analysed composite products manufactured in Australia. It took into account raw materials manufactured in Australia as well as those imported from overseas. The finished composite products manufactured overseas and then imported to Australia were not part of this project.

The project was a multi-partner project, comprising composites manufacturers, materials suppliers, 'research and development' agencies and an 'education and training 'agency.

The steering committee included:

- Ampelite Fibreglass Pty Ltd
- Boeing Research & Technology Australia
- B-Pods Pty Ltd (Tractile)
- Centre of Excellence in Engineered Fibre Composites (CEEFC)
- Exel Composites
- Mustang Marine Australia Pty Ltd
- Wagners Composite Fibre Technologies Manufacturing Pty Ltd
- Manufacturing Skills Australia

Additional support was provided by the following materials suppliers:

- Nupol Composites
- Colan Australia
- Toho-Tenex

The cradle-to-factory and the cradle-to-grave analyses were conducted to calculate the embodied energy for the composites materials and composite products. Therefore, the system boundary of the analyses is defined as the objects, scopes and assumptions of the analyses in the following sections. In addition, the embodied energy calculation methodology is also presented to illustrate the calculation approach and the expected outcome.

1.2 System boundary of the cradle-to-factory analysis

1.2.1 Objectives

1. The cradle-to-factory analysis was aimed to assess the embodied energy of the raw materials, which is a kilogram of the fibre composite materials.
2. The input-output model of the cradle-to-factory analysis was developed for the incurred raw materials, energy and waste during the processes of raw material extraction and transportation of raw materials. These two processes were the two main embodied energy sources of the cradle-to-factory analysis.

1.2.2 Scopes

The objectives of the cradle-to-factory analysis were achieved successfully under the following scopes:

1. The cradle-to-factory analysis assessed five fibreglass composites and one carbon fibre composite from six participant composites companies as listed in Table 1.1.

No	Participant composites company	Composite material
1	B-Pod (Tractile) Pty Ltd	Glass reinforced plastic
2	Ampelite Fibreglass Pty Ltd	Glass reinforced plastic
3	Mustang Marine Australia Pty Ltd	Glass reinforced plastic
4	Exel Composites	Glass reinforced plastic
5	Wagners Composite Fibre Technologies (CFT) Manufacturing Pty Ltd	Glass reinforced plastic
6	Boeing Research and Technology	Carbon fibre reinforced plastic

Table 1.1: Composite materials of the cradle-to-factory analysis

2. The input-output model of the raw materials that require in making a kilogram of the fibre composite material was developed for all composite materials in Table 1.1. Six fibre composite materials were modelled in a spreadsheet model. The model of the cradle-to-

factory analysis showed the materials, energy and waste flows during the two main embodied energy sources as shown in Figure 1.1. The embodied energy sources were the raw material extraction and the transportation of the raw materials from suppliers to composite companies. As shown in Figure 1.1, the input is the material and energy that were required in the two embodied energy sources. The output is the emission substances and waste that were incurred during the operation of these two embodied energy sources.

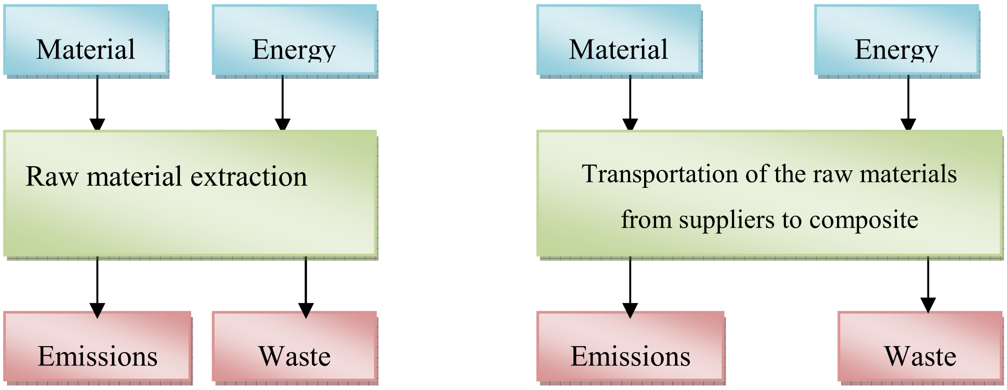


Figure 1.1: Input-output model of the cradle-to-factory analysis

1.2.3 Input data assumptions

The cradle-to-factory analysis aimed to assess the raw materials, which use in fabricating a kilogram of the six fibre composite materials. To achieve this task, the assumptions were made for the required input data of the cradle-to-factory analysis as illustrated in Table 1.2. In general, the participant composites companies provided the majority of the input data for the raw materials which are the types and the quantities of the raw materials, the associated transportation types and the travel distance from suppliers to the composites manufacturers. The unavailable input data as marked with the asterisk sign in Table 1.2 was obtained from literature reviews and the databases of the libraries from the Life Cycle Assessment software, SimaPro 7.1.8. The databases from the Life Cycle Assessment software, SimaPro 7.1.8 are also given in Table 1.3.

<table>
<tr><th>Life cycle stage</th><th>Embodied energy sources</th><th>Assumptions of the input data</th><th>Data source</th></tr>
<tr><td colspan="4">Cradle-to-factory: the embodied energy of the raw materials in making 1 kg of fibre or fibre or carbon fibre reinforced plastics.</td></tr>
<tr><td rowspan="2">Material: Raw materials for 1 kilogram of composite material</td><td>Raw material extraction</td><td>-Material types
-Material quantities</td><td>Composites companies data such as the material safety datasheet (MSDs)*</td></tr>
<tr><td>Transportation of the raw materials</td><td>-Transportation types
-Distances from suppliers to the companies.</td><td>Suppliers address, the composites manufacturing plant address, road and water transportation of each raw material*</td></tr>
</table>

Table 1.2: Input data Assumptions of the cradle-to-factory analysis

Databases	Australia Data 2007, BUWAL 250, Data Archive, ETH-ESU 96, Franklin 96, IDEMAT2001 and Industry data

Table 1.3: Databases list from the SimaPro 7.1.8 software

1.3 System boundary of the cradle-to-grave analysis

1.3.1 Objectives

1. The cradle-to-grave analysis was aimed to assess the embodied energy of the life cycle of the six composite products which was made of six fibre composite materials as analysed in the cradle-to-factory analysis.
2. The input-output model of the cradle-to-grave analysis was developed for the incurred materials, energy and waste during the processes of materials, manufacturing process, usage and disposal life cycle stages of the composite products.
3. The embodied energy of the composite products and the traditional products that are made from the traditional materials were analysed and compared.

1.3.2 Scopes and limitations

The objectives of the cradle-to-grave analysis were achieved under the following scopes:

1. The cradle-to-grave analysis was carried out for six composite products, which were made by six composites manufacturers as listed in Table 1.4. In practice, these composite products may require additional raw materials for their applications such as the roof tile would require battens and screws to assembling the roofing system. Therefore, Table 1.5 shows the utilisation of the additional materials for the composite products.

No	Participant company	Composite products	Traditional products
1	B-Pod (Tractile) Pty Ltd	1 square metre of roof tile	- Concrete tile - Galvanised steel sheet
2	Ampelite Fibreglasss Pty Ltd	1 square metre of Wonderglas GC and Webglas GC	- Galvanised steel sheet
3	Mustang Marine Australia Pty Ltd	Mustang 430 powerboat hull	Aluminium (5086)
4	Exel Composites	1 linear metre of Exel I-Beam	Cold-formed stainless steel (316)
5	Wagners CTF Manufactures Pty Ltd	A 2.5 linear metre power-pole cross-arm	Sawn hardwood timber
6	Boeing Research and Technology	An aircraft hinge fitting	Cold-formed titanium

Table 1.4: Descriptions of the cradle-to-grave analysis for assessing the composite products and their comparable products.

No	Composite products	Only composite material included in the product	The composite material and additional materials included in the product
1	1 square metre of roof tile		✓ (battens and fasteners)
2	1 square metre of roof sheet		✓(battens and fasteners)
3	A powerboat hull		✓ (plywood and foam barrier)
4	1 linear metre of I-Beam	✓	
5	A 2.5 linear metre power-pole cross-arm		✓ (connections)
6	An aircraft hinge fitting	✓	

Table 1.5: Summary of materials used in the applications of the composite products

2. The input-output model of the cradle-to-grave analysis for each composite product is developed as a spreadsheet model. The model in Figure 1.2 shows the input and the output of four main embodied energy sources that require in making a composite product. The embodied energy sources are the life cycle stages of the composite product which are materials, manufacturing process, usage and end-of-life. The input in Figure 1.2 is the material and energy that is required in the four embodied energy sources whereby the output is the emission substances and the waste that is incurred during these four embodied energy sources.

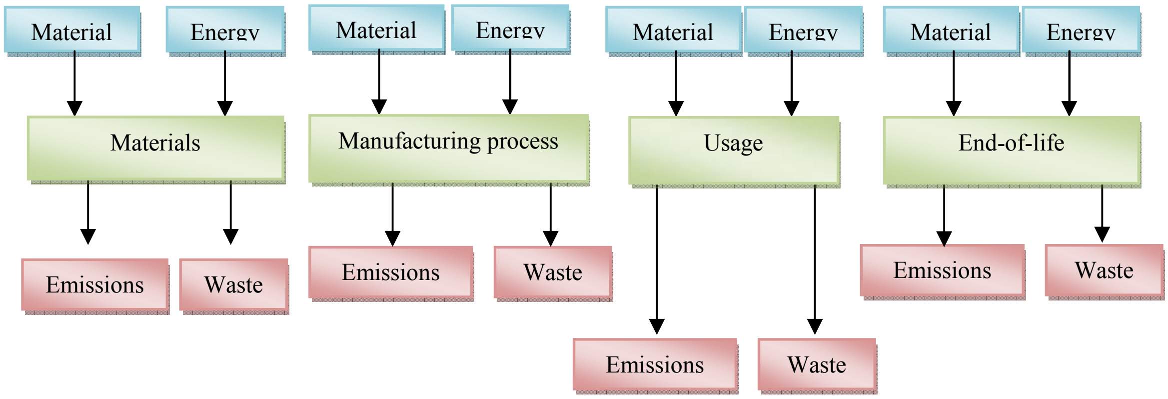


Figure 1.2: Four main embodied energy sources of input-output model.

1.3.3 Input data assumptions

The compatible products that are made from the traditional products are six traditional products as shown in Table 1.6.

Life cycle stage	Embodied energy sources	Assumptions of the input data	Data source
Cradle-to-grave: The embodied energy of a product life cycle that is made from a composite material which is used in the cradle-to-factory analysis.			
For products made from only composite materials Material: Total amount of raw materials for making a product	Raw material extraction and transportation of the raw materials	Similar to the cradle-to-factory analysis in Table 1.2 and multiply with the total amount of composite material	Similar to Tables 1.2 and 1.3
For products made from composite materials and other materials Material: Total amount of raw materials for making a product	Raw material extraction and transportation of the raw materials	Composite material part: Similar to the cradle-to-factory analysis in Table 1.2 and multiply with the total amount of composite material. Other material part: - Material types - Material quantities - Transportation types - Distances from suppliers to the companies.	Similar to Tables 1.2 and 1.3
Manufacturing process	Processes that are required in making the product such as cutting for a metre in length, welding for 0.05 metre	-Process types -Process quantities	Databases in Table 1.3
Usage	Energy required during the usage such as transportation for the installation, maintenance activities.	- Energy types - Energy quantities	Databases in Table 1.3
Disposal	Disposal scenarios of a product such as 100% landfill for the composites materials and 70% recycling for steel and 65% recycling for aluminium	- Disposal types - Disposal quantities	Databases in Table 1.3

Table 1.6: Input data assumptions of the cradle-to-grave analysis

1.4 The embodied energy methodology and expected outcome

1. The embodied energy is calculated by using three Life Cycle Impact Assessment methods which are available in the Life Cycle Assessment software, SimaPro 7.1.8. These methods are the Cumulative Energy Demand version 1.04 (CED 1.04), the IPCC GWP 100a version 1.00 and the Eco-Indicator 99 H/A methods. These methods assess the embodied energy in three different environmental aspects. The selection of the methods and their calculation approach are summarised in Table 1.7.
2. The expected outcome for the cradle-to-factory and the cradle-to-grave analyses from the three methods are the embodied energy results as given in Table 1.7. Furthermore, six air pollutants are additionally calculated.
3. The interpretations of the results are presented in Figure 1.3.

<table>
<tr><th colspan="5">EMBODIED ENERGY CALCULATION TOOL</th></tr>
<tr><th>Embodied Energy Analysis</th><th colspan="4">Scopes and Assumptions</th></tr>
<tr><td>Embodied energy assessment tool</td><td colspan="4">The Life Cycle Impact Assessment methods from the LCA software, SimaPro 7.1.8 software.</td></tr>
<tr><td>Selection of the Life Cycle Impact Assessment methods</td><td colspan="4">The selection of these methods was based on the generic embodied energy analysis which is often based on the input-output model that is used to quantify the primary energy sources and often expressed in MJ and in kg of CO_2 units. In addition, as the two values from the Cumulative energy demand version 1.04 and the IPCC GWP 100a version 1.00 methods only represent the embodied energy in terms of the primary energy consumption and the impacts from the climate change respectively. Therefore, the points value is also given. This value is calculated from Life Cycle Assessment which considers the impacts on human health, the ecosystem quality and resource use. The points value is calculated from the Eco-Indicator 99 H/A version 2.03 method.</td></tr>
<tr><th colspan="5">LIFE CYCLE IMPACT ASSESSMENT METHODS</th></tr>
<tr><th rowspan="2">Method</th><th rowspan="2">Calculation Approach and unit</th><th colspan="3">Embodied Energy Results</th></tr>
<tr><th>Cradle-to-factory</th><th>Cradle-to-grave</th><th>Amount of conventional air pollutions</th></tr>
<tr><td>Cumulative energy demand version 1.04</td><td>Calculation: Calculates the embodied energy in terms of the consumption of the primary energy sources such as fossil fuels, minerals, renewable energy.
Unit: MJ_{eq}</td><td>MJ_{eq} per kg</td><td>MJ_{eq} per product</td><td rowspan="3">Carbon monoxide (CO)
Carbon dioxide (CO_2)
Nitrogen dioxide (NO_2)
Sulphur dioxide (SO_2)
Unspecified particulate
Volatile organic compounds (VOC)</td></tr>
<tr><td>IPCC GWP 100a version 1.00</td><td>Calculation: Calculates the greenhouse gas emissions which impact the global warming.
Unit: kg CO_{2eq}</td><td>kg CO_{2eq} per kg</td><td>kg CO_{2eq} per product</td></tr>
<tr><td>Eco-Indicator 99 H/A version 2.03</td><td>Calculation: calculates as the environmental performance indicator as a single score. This is a comprehensive Life Cycle Assessment analysis which considers human health, the ecosystem quality and resource use impacts.
Unit: points of a single score</td><td>points per kg</td><td>points per product</td></tr>
</table>

Table 1.7: Summary of calculation tools and expected outcome for the embodied energy analysis

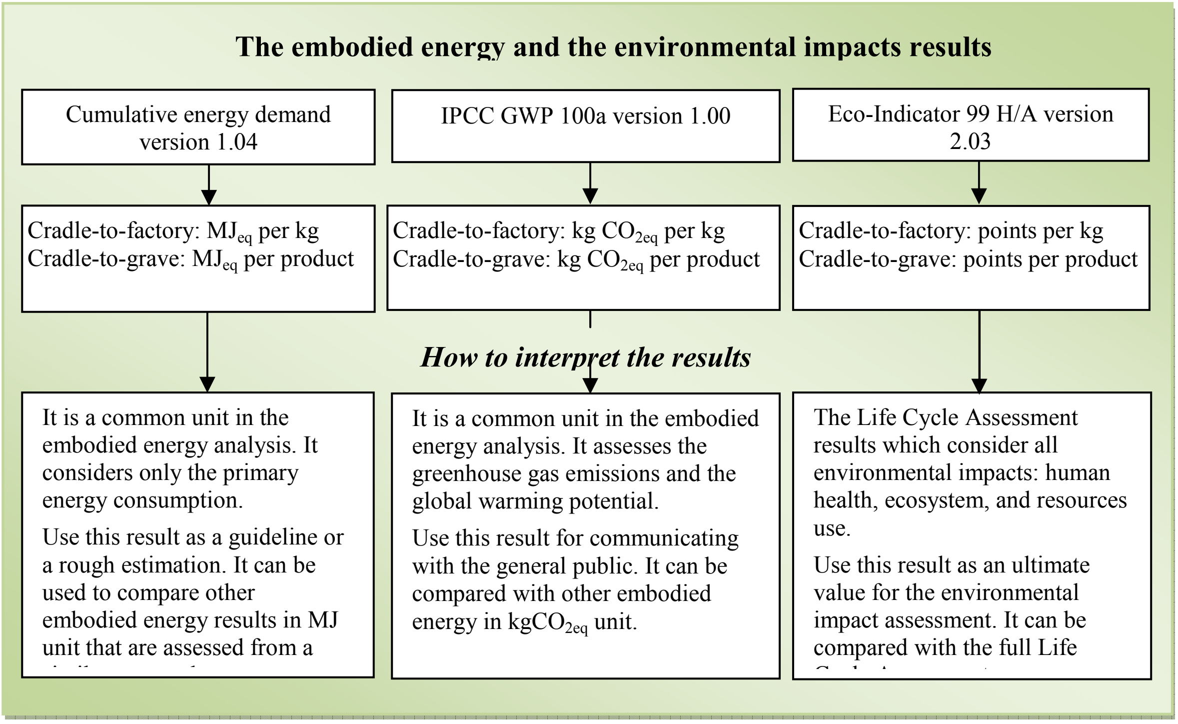


Figure 1.3: Diagram of How to interpret the embodied energy results

1.5 Report outline

The report outline is presented in Figure 1.4. The contents of each chapter can be described as follows.

Executive summary presents the entire contents of this report in brief where the aim, scopes, embodied energy analysis approach, results of the cradle-to-factory and the cradle-to-grave analyses as well as discussion, conclusion and recommendations are included.

Chapter 1, Project overview, presents the background of this study that aims to calculate the embodied energy of six composites materials and thirteen composite products including their comparable products.. The main contents in this chapter include the objectives, scopes, assumptions, methodology and expected outcome of the study.

Chapter 2, Embodied energy analysis, delineates the methodology used in this study to quantify the embodied energy of the composites materials and the composite products. This chapter starts with an introduction of the Life Cycle Assessment method which is often used to calculate the environmental impacts of a product life cycle. Three Life Cycle Impact Assessment methods and their results are presented as the main embodied energy calculation tools for this study. These methods are the Cumulative Energy Demand, IPCC2007 GWP100a and Eco-Indicator 99 H/A methods. Subsequently, the cradle-to-factory and the cradle-to-grave analyses are presented in order to familiarise the main approaches used to perform the embodied energy analysis of the composite materials and the composite products. In addition, the methodology overview is given to illustrate the procedures which were utilised to conduct the embodied energy analysis in order to achieve the objectives of the study.

The data collection summary, data quality and uncertainly as well as the input-output model are also presented to explain the procedures used whilst conducting the study.

Chapters 3 to 8 demonstrate the embodied energy results for the analysed composite materials and the composite products for each participant composites manufacturers in a sequence as given in Figure 1.4.

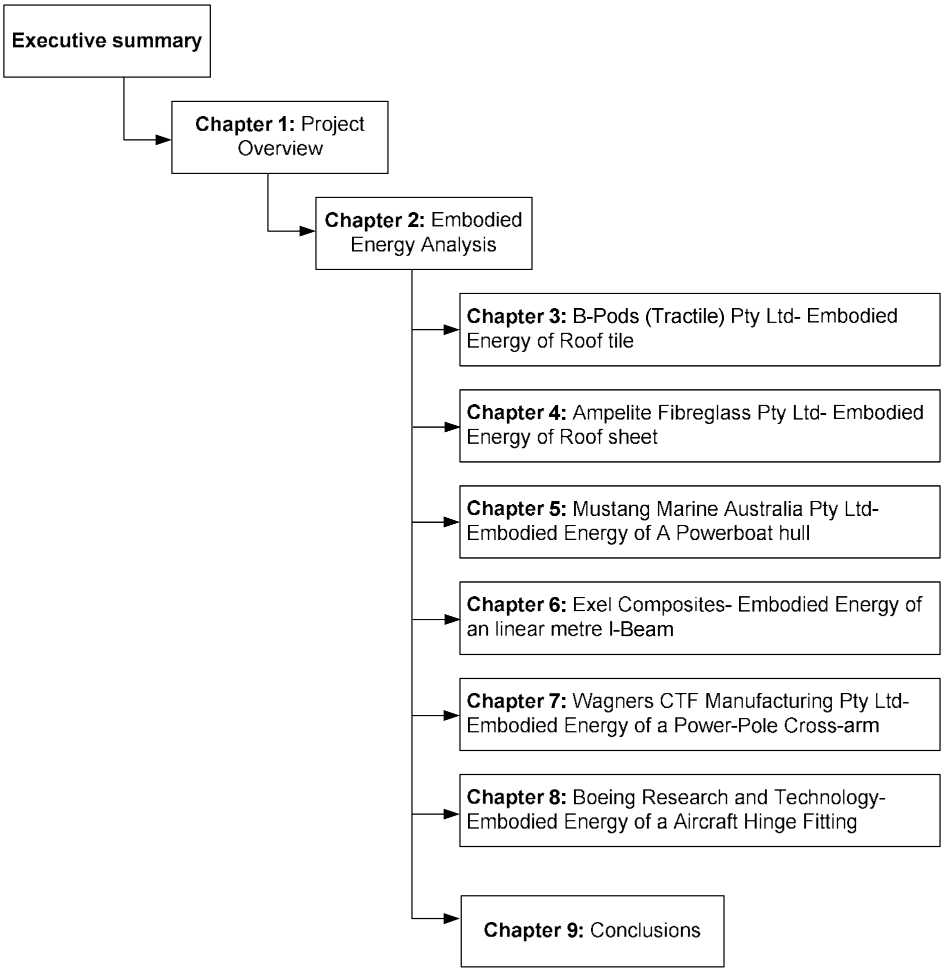


Figure 1.4: Report outline

The chapters are:

Chapter 3: B-Pods (Tractile) Pty Ltd-Embodied Energy of Roof Tile

Chapter 4: Ampelite Fibreglass embodied energy of roof sheet

Chapter 5: Mustang Marine Australia Pty Ltd

Chapter 6: Exel Composites

Chapter 7: Wagners Composite Fibre Technologies Manufacturing Pty Ltd

Chapter 8: Boeing Research & Technology Australia

Each chapter present an introduction of the composite products and followed by the methodology which includes the overview, scopes, assumptions and the interpretation of the results. Subsequently, the descriptions of the composites and traditional products are presented and defined as the input data for the embodied analysis. The embodied energy results are discussed and concluded in the last section of each chapter.

Chapter 9, Conclusion, summarises the embodied analysis and results of the Composites: Calculating Their Embodied Energy Study as a whole.

Appendices A to D are provided in the last section of this report for the air conventional emission results, the technical manual for the material and energy flow spreadsheet model, their sensitivity analysis and the database background for the embodied energy analysis.

1.6 Conclusion

This chapter provided an overview of the project, which aims to investigate on the embodied energy of the composites materials and composite products. In this project, two analyses were conducted which are the cradle-to-factory and the cradle-to-grave analyses. The objectives, scopes and input assumptions of these analyses were presented.

In general, the cradle-to-factory analysis was aimed to assess the embodied energy of the raw materials, which are used in making 1 kilogram of the composite material. The cradle-to-grave analysis was to calculate the embodied energy for the life cycle of a composite product that was manufactured by using fibre or carbon fibre composites and traditional materials. Consequently, the comparisons of the products, which are made in different materials, are compared.

The embodied energy calculation methodology was also illustrated by presenting the three Life Cycle Impact Assessment methods, namely the Cumulative Energy Demand version 1.04 (CED 1.04), the IPCC GWP 100a version 1.00 and the Eco-Indicator 99 H/A methods. The expected outcome of this study is the embodied energy results in a unit of MJ_{eq} and kg CO_{2eq} as well as the total environmental impact result which expressed in a unit of points. The last section of the chapter outlined the contents of this report which includes an introduction, methodology, results and conclusion.

CHAPTER 2

EMBODIED ENERGY ANALYSIS

2.1 Introduction

Chapter 1 addressed the main objectives, scopes, assumptions and report outline. Therefore, this chapter presents the methodology of the embodied energy analysis of this study. Firstly, background of the Life Cycle Assessment (LCA) background is introduced as a methodology to assess the environmental impact. Further, three Life Cycle Impact Assessment methods are presented briefly as these methods will be used as a tool to calculate the embodied energy for the entire study. Subsequently, an overview of the methodology of this embodied energy study is described whereby the data collection is summarised into input data for the cradle-to-factory and the cradle-to-grave analyses. Furthermore, the input-output models of the analyses are presented to illustrate the materials and the energy flows during the activities that are involved in making of the raw materials of composites materials and the life cycle of the composite products.

2.2 Life Cycle Assessment

LCA is a tool to assess the environmental impact of a product's life cycle as shown in Figure 2.1. This methodology is also known as a 'cradle-to-grave' analysis which calculates materials and energy flow analysis of the product life cycle stages as shown in Figure 2.1.

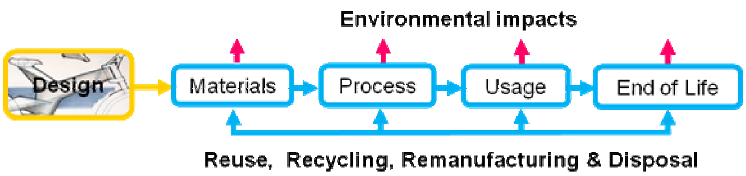


Figure 2.1: Product life cycle stages

Theoretically, LCA has four basic stages which are:

1. Goal definition and scoping
2. Life Cycle Inventory (LCI) Analysis
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation.

The first stage is defining the unit function of an industrial product for the product life span. The second stage is the inventory analysis, which transforms the data input of materials and energy sources into an emission substance amount as Life Cycle Inventory (LCI) results. The third stage is the Life Cycle Impact Assessment (LCIA) method that converts the LCI results into the environmental impact results. Furthermore, the results can also be estimated at the midpoint which is expressed as the impact categories or the endpoint level of the LCIA modelling step and then it can be summarised into a single index or a single score which has a variety of units as it depends on which LCIA method is employed in the analysis. Finally, the interpretation stage is to present and analyse the results.

➢ *LCIA Methods*

Whilst a number of LCIA methods have been developed over the past few decades, the Cumulative Energy Demand (CED), IPCC2007 GWP100a (IPCC) and Eco-indicator 99 H/A (EI99) methods were selected for this study.

- Cumulative Energy Demand version 1.04 method (CED1.04)

  In brief, the CED1.04 method is often used to assess the energy consumptions or flows throughout the entire life cycle of a good or a service. The MJ_{eq} is calculated based on different energy resources namely the ‘non renewable fossil’, ‘non-renewable nuclear’, ‘renewable biomass’, ‘renewable wind, solar, geothermal’ and ‘renewable water’. The CED1.04 method produces the results in a unit of MJ_{eq}.

- IPCC 2007 GWP 100a version 1.00 method (IPCC1.00)

  The IPCC method is based on the Global Warming Potential (GWP) factors from the Inter Panel on Climate Change (IPCC) where “the GWPs are an index for estimating relative global warming contribution due to the atmospheric emission of a kg of a particular greenhouse gas compared to the emission of a kg of carbon dioxide”. The IPCC method is available in three different time horizons which are 20, 100 and 500 years in order to analyse the effects of atmospheric lifetime of the different gases. For instance, during 100 years, while CO_2 has a GWP of 1 and methane has the GWP of 25 which means 1 kilogram of methane has a potential to cause climate change 25 times more than CO_2. The IPCC1.00 method produces the results in a unit of kg CO_{2eq}.

- Eco-Indicator 99 H/A version 2.03 method (EI99 method)

  The EI99 method is also used along with the CED1.04 and IPCC1.00 methods. This methodology delivers a single score, which is a comprehensive method based on the scientific background using several analyses. These consider the environmental impacts in all aspects namely human health, the ecosystem and resource use as shown in Figure 2.2.

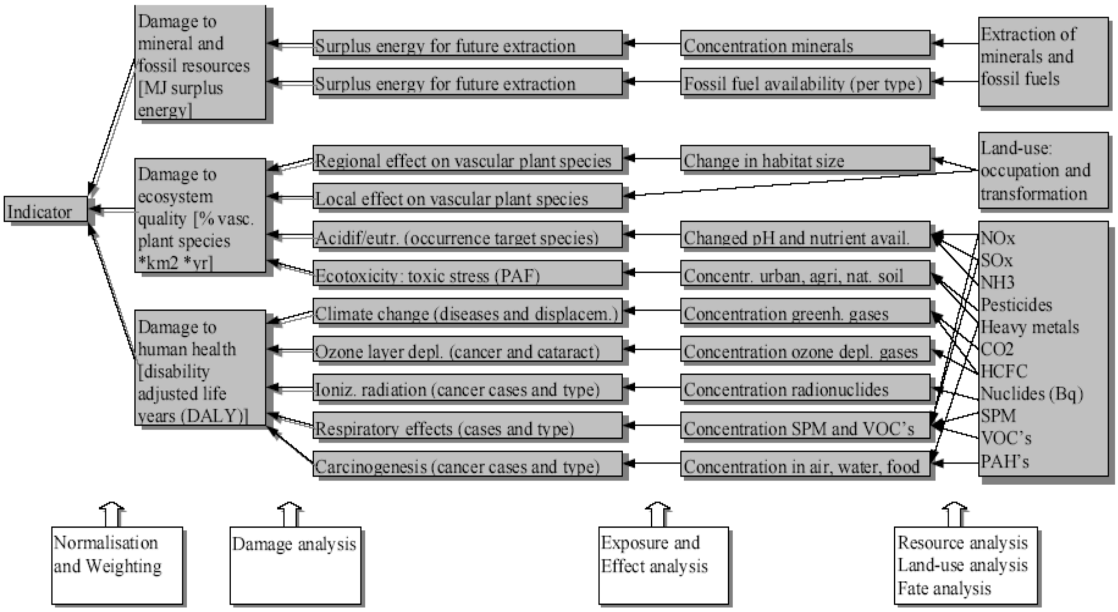


Figure 2.2: Eco-Indicator 99 LCIA method[1]

- *Expected outcome of Life Cycle Assessment*

The expected outcomes of the LCA results for this project are presented as follows.

- Amount of emission substances: Conventional air pollution or GHG emissions namely, CO, CO_2, NO_2, SO_2, Particulate (unspecified) and VOC
- Single score: MJ_{eq}, kg CO_2 and points (pts)

Furthermore, Table 2.1 also summarises the calculation approach and the results of the three methods for the Life Cycle Impact Assessment methods. These methods generated the embodied energy results for these analyses in the units of MJ_{eq} and kg CO_{2eq} and the total environmental impact in a unit of points per kg as well as in units of MJ_{eq}, kg CO_{2eq} and points per product or application. Therefore, Figure 2.3 is given to provide additional information to aid in how to interpret these results.

[1] Goedkoop, M., Spriensma, R., "The Eco-indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment, Methodology Report," PRé Consultants B.V., The Netherlands 2001.

EMBODIED ENERGY CALCULATION TOOL	
Embodied Energy Analysis	**Scopes and Assumptions**
Embodied energy assessment tool	The Life Cycle Impact Assessment methods from the LCA software, SimaPro 7.1.8 software.
Selection of the Life Cycle Impact Assessment methods	The selection of these methods was based on the generic embodied energy analysis which is often based on the input-output model that is used to quantify the primary energy sources and often expressed in MJ and in kg of CO_2 units. In addition, as the two values from the Cumulative energy demand version 1.04 and the IPCC GWP 100a version 1.00 methods only represent the embodied energy in terms of the primary energy consumption and the impacts from the climate change respectively. Therefore, the points value is also given. This value is calculated from Life Cycle Assessment which considers the impacts on human health, the ecosystem quality and resource use. The points value is calculated from the Eco-Indicator 99 H/A version 2.03 method.

<table>
<tr><th colspan="5">LIFE CYCLE IMPACT ASSESSMENT METHODS</th></tr>
<tr><th rowspan="2">Method</th><th rowspan="2">Calculation Approach and unit</th><th colspan="3">Embodied Energy Results</th></tr>
<tr><th>Cradle-to-factory</th><th>Cradle-to-grave</th><th>Amount of conventional air pollutions</th></tr>
<tr><td>Cumulative energy demand version 1.04</td><td>Calculation: Calculates the embodied energy in terms of the consumption of the primary energy sources such as fossil fuels, minerals, renewable energy.
Unit: MJ_{eq}</td><td>MJ_{eq} per kg</td><td>MJ_{eq} per product or application</td><td rowspan="3">Carbon monoxide (CO)
Carbon dioxide (CO_2)
Nitrogen dioxide (NO_2)
Sulphur dioxide (SO_2)
Unspecified particulate
Volatile organic compounds (VOC)</td></tr>
<tr><td>IPCC GWP 100a version 1.00</td><td>Calculation: Calculates the greenhouse gas emissions which impact the global warming.
Unit: kg CO_{2eq}</td><td>Kg CO_{2eq} per kg</td><td>kg CO_{2eq} per product or application</td></tr>
<tr><td>Eco-Indicator 99 H/A version 2.0</td><td>Calculation: calculates as the environmental performance indicator as a single score. This is a comprehensive Life Cycle Assessment analysis which considers human health, the ecosystem quality and resource use impacts.
Unit: points of a single score</td><td>points per kg</td><td>points per product or application</td></tr>
</table>

Table 2.1: Summary of calculation tools and results for the embodied energy analysis

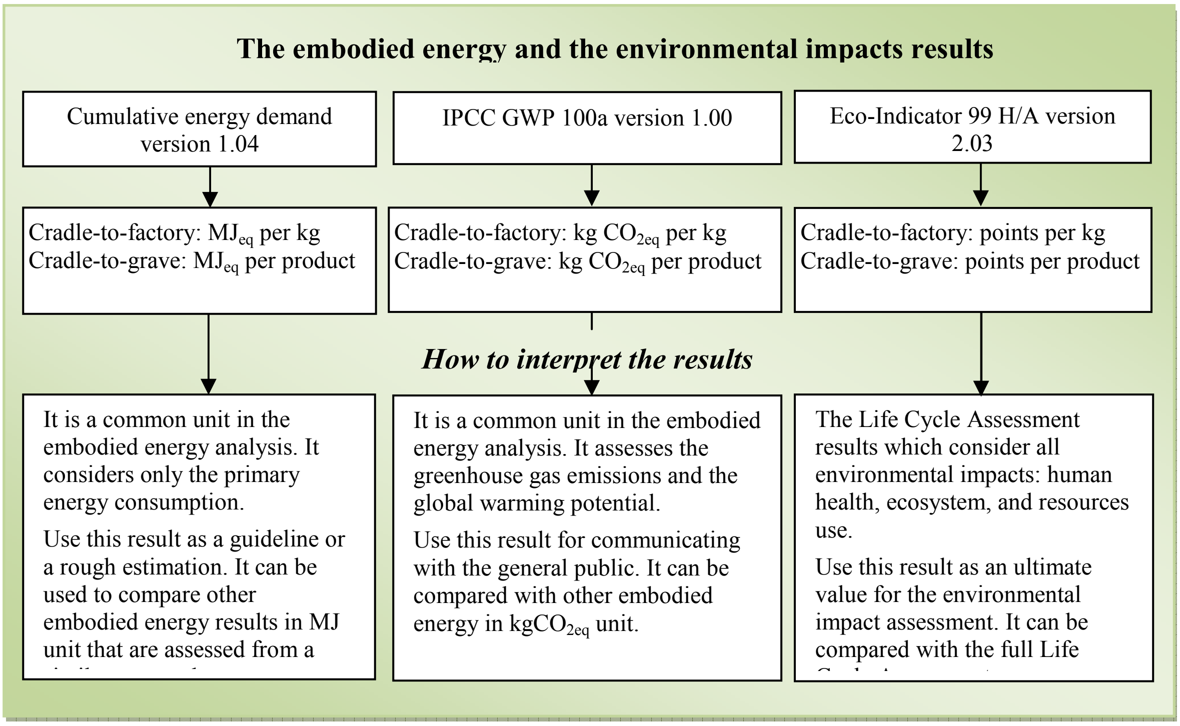


Figure 2.3: Diagram of How to interpret the embodied energy results

2.3 Embodied Energy Analysis

The embodied energy analysis in this study comprises of cradle-to-factory and the cradle-to-grave analyses as shown in Figure 2.4. These analyses employ the Life Cycle Impact Assessment methods to assess the embodied energy of all life cycle stages as shown in Figure 2.4. The methodology of these two analyses is described briefly as follows.

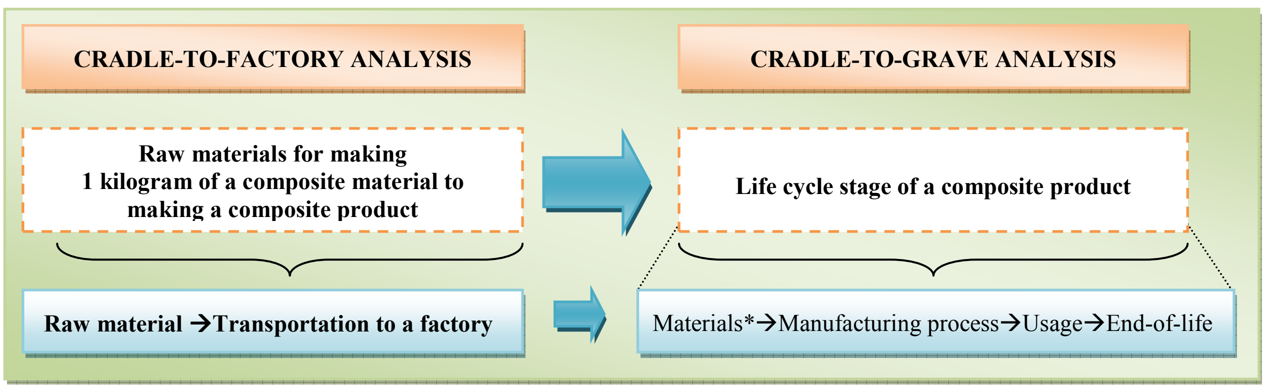


Figure 2.4: Scopes of the cradle-to-factory and the cradle-to-grave analyses.

Firstly, the cradle-to-factory analysis assesses the embodied energy in making 1 kilogram of a composite material as presented in the left portion of Figure 2.4. This analysis focuses on two main embodied energy sources. They are the raw material extraction and the transportation of raw materials from the supplier to a composite manufacturer. The asterisk sign next to the word 'Materials' in Figure 2.3 indicates that the embodied energy result from this analysis will be used as the input data for the materials stage in the next analysis.

Secondly, the cradle-to-grave analysis as shown in Figure 2.4 calculates the life cycle of a composite product. For comparison purposes this analysis technique is also performed on a traditional product with the same application. The life cycle stages of these products are presented on the right hand side of Figure 2.4 where:

- The materials stage is the total raw materials that are used in making the targeted products;
- The manufacturing process stage comprises the processes involved in making the targeted products;
- The usage stage consists of the activities that occur after the targeted products are manufactured i.e. the installation and maintenance activities, until the product is disposed of.
- The end-of-life stage is the disposal scenario which includes the transportation of the targeted products to the disposal site and the disposal process.

Finally, the embodied energy and the environmental impacts results from the cradle-to-factory analysis are discussed and the hot spots identified. For this project a hot spot is defined as the raw materials and/or suppliers which have a high contribution to the embodied energy results. The hot spots analysis was conducted to make further suggestions in order to minimise or eliminate the identified raw materials and/or suppliers. Subsequently, the embodied energy results from the cradle-to-grave analysis of the composite products were analysed and compared with the life cycle of the traditional products which are made of the traditional materials such as stainless steel and aluminium.

2.4 Methodology Overview

The methodology of the embodied energy analysis was conducted in accordance with Figure 2.5. The aim of the project was achieved by utilising a systematic methodology which can be described as follows:

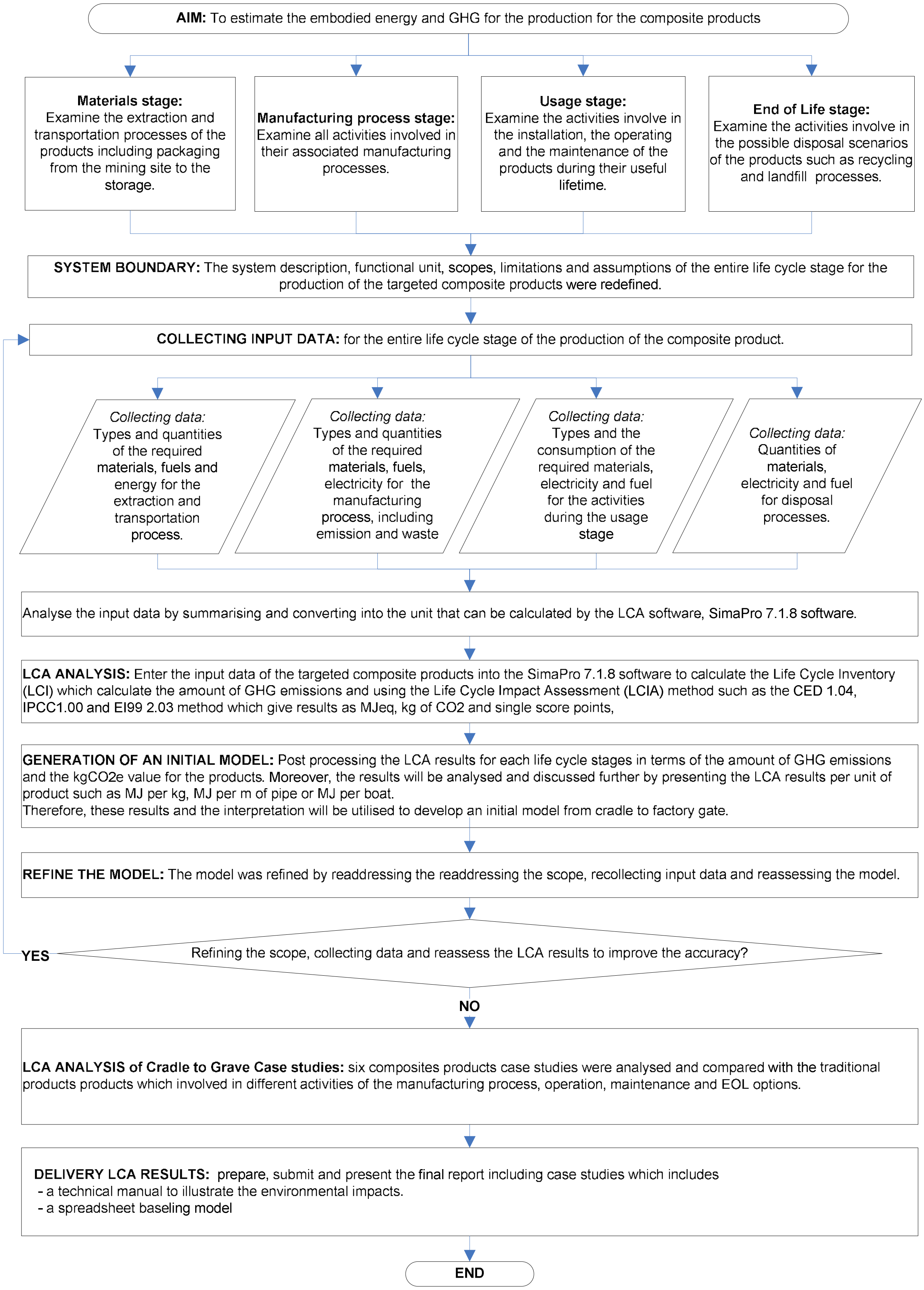


Figure 2.5: Methodology of embodied energy analysis

Firstly, all processes or activities that are involved in the life cycle of the composite products including the materials, manufacturing, usage and end-of-life cycle stages were examined as illustrated in

Figure 2.4. The consideration mainly focused on the materials, fuels and energy or electricity consumed during the life cycle stages as demonstrated in the second row of Figure 2.5. Subsequently, the system boundaries or descriptions were defined. This included the development of the model framework, tasks, scope, limitation(s), assumptions as well as the functional unit of the composite products.

Secondly, the required input data for the LCA analysis was collected for each life cycle stage where the input data is mainly in terms of the quantities and the types of raw materials, energy or electricity, the possible EOL options, the types of transportation, their travel distance and carriage weight. These input data were attained to analyse and to understand the materials and the energy flow of the production of composite products. Therefore, the data was collected extensively by primarily using the input data which were provided by the companies as presented in Figure 2.5.

Further information was collected by the companies via measurement from the production line such as the electricity and the water consumption as well as the emissions and wastes. Subsequently, the collected data was analysed, summarised and converted into units that can be used to carry out the LCA analysis by using the SimaPro 7.1.8 software. For instance, the input data requirement for the transportation was tkm which considers both distance and the weight carriage. Therefore, the distance in km was multiplied with the weight of the materials in the unit of tonne to give the tkm input data for the software.

Thirdly, the LCA analysis was performed using the converted input data and the selected Life Cycle Impact Assessment (LCIA) methods namely the CED 1.04, the IPCC 1.00 and the EI99 2.03 methods to produce the embodied energy results in terms of MJ_{eq}, kg CO_{2eq} and points respectively. Moreover, the analysis also generated the results for the amount of emissions. Consequently, the results were further analysed by converting them into LCA results per unit of a product. In this project, the LCA results can be presented as MJ_{eq}, kg CO_{2eq} and points per kg, square metre, powerboat hull, linear metre, power-pole cross-arm and aircraft hinge fitting.

Fourthly, the model as shown in Figure 2.5 was refined by readdressing the scope, recollecting data and reassessing the model. Subsequently, the refined model was implemented in thirteen case studies to demonstrate the benefits of using the composite products over traditional material products such as concrete tile, steel sheet, cold-formed aluminium, cold-formed stainless steel, sawn hardwood timber and cold-formed titanium. For instance, the advantages of the composite products such as the reduction in fuel consumption due to their light weight or the reduction in material consumption due to their corrosive resistance was addressed.

In addition, 'hot spots' were also identified for future improvement of the targeted composite products. For example, the impacts of the transportation for the raw materials might be improved by selecting local suppliers or energy consumption can be reduced from some particular processes. Consequently, the final report was prepared to present the generic embodied energy results of the case studies for all participating companies and institutions as shown in Figure 2.5. Whereby, the detailed spreadsheet baseline model and the detailed technical manual were delivered to the corresponding company. The spreadsheet model of the embodied energy is proficient to calculate both cradle-to-factory and cradle-to-grave where the user can alter the input data and regenerate all embodied energy results including the emissions in each life cycle stage.

2.5 Data Sources Summary

The collection of data is one of the critical parts of this project as it has tremendous consequences for the precision and accuracy of the model. Figure 2.6 and Table 2.2 present a summary of the input data required from the six composite manufacturers and the selected Life Cycle Inventory databases from the Life Cycle Assessment software, SimaPro 7.1.8, for the cradle-to-factory and the cradle-to-grave analyses.

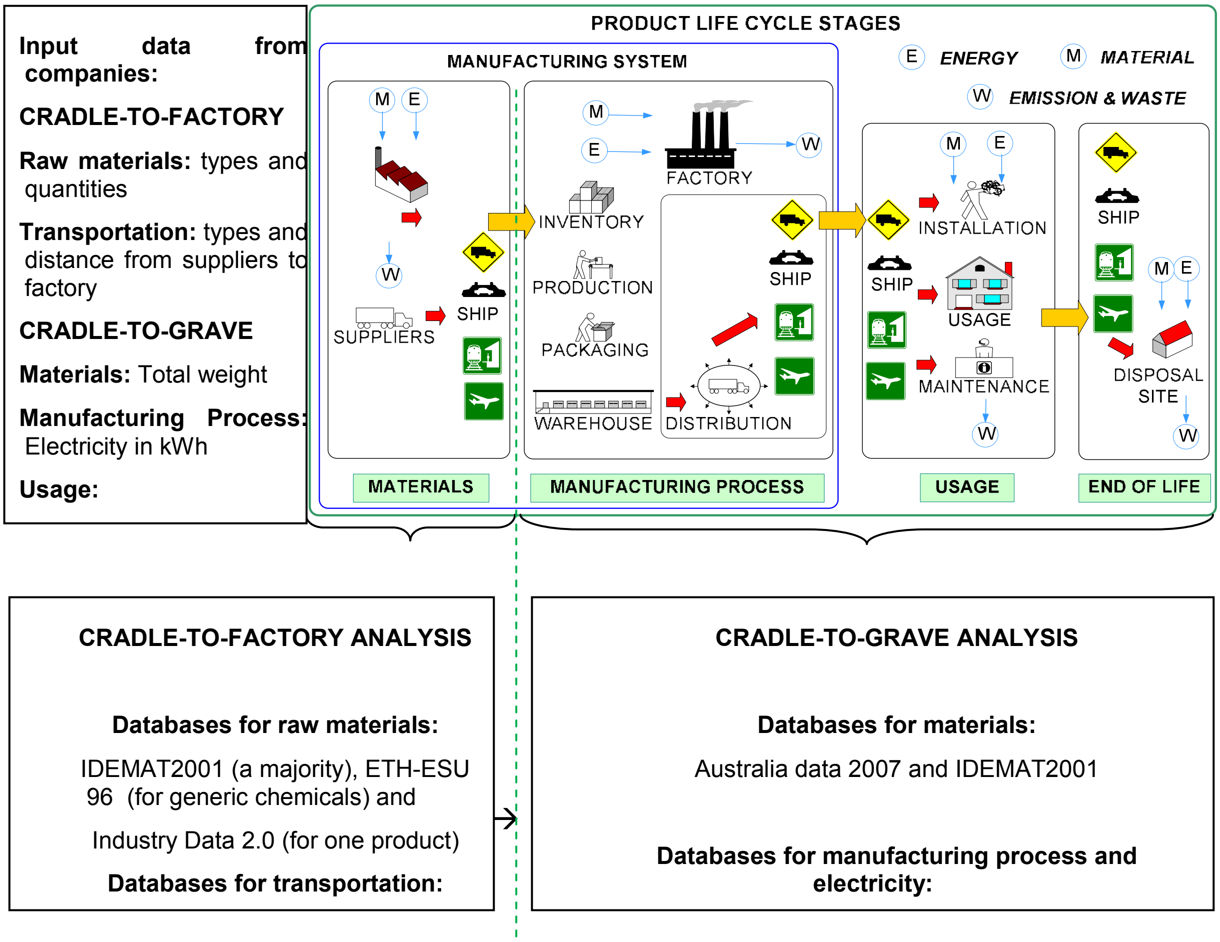


Figure 2.6: Detailed input data required for Life Cycle Assessment.

Company	CRADLE-TO-GRAVE					
	CRADLE-TO-FACTORY					Case Studies
	Amount in 1 kilogram of glass or carbon fibre reinforced plastics					Making a product
	Fibre types	**Resin types**	**'Other' materials**	**Raw material extraction**	**Transportation from supplier to factory**	**Material, Manufacturing process, distribution, installation, usage, maintenance, end-of-life process**
B-Pods Pty Ltd (Tractile)	E glass	Polyester	Pigment, fillers, and retardants	Based on B-Pods data and modified from IDEMAT2001	Road and water transportation types from Australia and overseas. The distance was measured using an online maps, Google. The road transportation based on Australian data 2007 databases	1 m^2 roof tile
Ampelite Fibreglass Pty Ltd	E glass	Polyester	Pigment, polyester film, gel coat and catalyst	Based on Ampelite data, modified from IDEMAT2001, Industry data 2.0 and Australian data 2007 databases		1 m^2 roof sheet
Mustang Marine Australia Services Pty Ltd	Four types of fibreglass	Polyester and vinyl ester	Catalysts and gel coat.	Based on Mustang Marine and modified from IDEMAT2001, Australian data 2007 and CPM databases		1 powerboat hull
Exel Composites	Two types of E glass	Vinyl ester	Pigment, fillers, catalysts and retardants.	Based on Exel coposites, modified from IDEMAT2001, ETH-ESU96 and Australian data 2007 databases		1 linear metre I-Beam
Wagners CFT Manufacturing Pty Ltd	Fibreglass	Vinyl ester	-	Based on Wagners, modified from IDEMAT2001 and Australian data 2007 databases		2.5 linear metre power-pole cross-arm
Boeing Research & Technology Australia	Carbon fibre	Epoxy	-	Based on Boeing R &T, modified from IDEMAT2001 and Australian data 2007 databases		1 aircraft hinge fitting

Table 2.2: Input data for the cradle-to-factory and the cradle-to-grave analyses

The input data for the cradle-to-factory and the cradle-to-grave analyses were obtained from the participant companies as shown in Figure 2.6 and Table 2.2. The input data for the cradle-to-factory analysis included the types and the quantities of the raw materials namely fibres, resins and the 'other' materials, the supplier's details, manufacturing locations and transportation types from the supplier to a factory. The input data was used to assess the embodied energy of the energy extraction of the raw materials and the transportation of raw materials for the cradle-to-factory analysis.

Subsequently, the input data of the cradle-to-grave analysis were the total quantities of required materials, energy consumption of the manufacturing process for both manufacturing process and the supporting systems of the manufacturing process, the distribution of the product to the customer, the installation, usage, maintenance system, disposal transportation and process. The majority of this input data was collected from the companies as shown in Figure 2.6.

Concurrently, the Life Cycle Inventory databases were also selected from the available libraries of the SimaPro 7.8.1 software. At the present time, the Australian data 2007, BUWAL250, ESU-ETH 96, Frankin USA 98, IDEMAT2001, and Industry data 2.0 were the available standard libraries from the software.[2] The Life Cycle Inventory libraries as shown in Figure 2.6 were selected by examining all the characteristics of the collected input data as shown in Table 2.3.

Life Cycle activities	Composite products	Traditional products
CRADLE-TO-FACTORY		
Raw materials	**Type:** 46 different materials from 6 products Fibre (fibreglass, carbon fibre) Resin (polyester, vinyl ester, epoxy) Chemicals (organic and inorganic for fillers, catalyst, additives, pigment **Quantity:** kg per kg of fibre composite or kg per a volume of production	**N/A**
Suppliers locations	**Supplier:** 36 suppliers are located in 10 countries from Australasia, Asia, Europe and US regions	Australian suppliers and manufacturers
CRADLE-TO-GRAVE		
Materials	**Type:** Tractile tile, Wonderglas GC, Webglas GC, Mustang Marine 430 hull, Exel I-Beam Wagners' power-pole cross-arm and Boeing's aircraft hinge fitting **Quantity:** kg of materials used for making a finished product	**Type:** Concrete tile, coated steel sheeting, Galvanised steel sheeting, Aluminium hull Stainless steel (316) I-Beam, Hardwood timber power-pole cross-arm, Titanium aircraft hinge fitting (from the USA) **Quantity:** kg of materials used for making a finished product
Manufacturing process	**Types:** Pultrusion, sheet moulding compound and molding processes **Quantity:** kWh of electricity consumption measured by the companies.	Type: Steel rolling, coated steel sheet, zinc coating, aluminium cold-transforming, steel cold transforming, sawing of wood production
Usage	**Installation:** In Australia Additional materials during the application such as screws and battens; Electricity for secondary process such as cutting and drilling; Transportation from manufacturer to a customer **Operation and maintenance:** Fuel consumption and transportation	**Installation:** In Australia Additional materials during the application such as screws and battens; Electricity for secondary process such as cutting and drilling; Transportation from manufacturer to a customer **Operation and maintenance:** Fuel consumption and transportation
End of Life	Transportation from a customer to the disposal site and disposal process in Australia	Transportation from a customer to the disposal site and disposal process in Australia

Table 2.3: Summary of input data characteristic of the composite and their comparable products

[2] The ecoinvent database is excluded in this list as it was not available in the SimaPro software version that was used for this project. Nevertheless, this database was also reviewed and found that it did not provide carbon fibre, one plastic film, stainless steel (316) and titanium in their database. Therefore, it was not included in this project.

As shown in Table 2.3, the first characteristic was that more than 50 raw materials were used in those fourteen products. These raw materials originated from ten different countries in four regions. Secondly, the input data of the manufacturing processes for the composite products were commonly obtained as the quantity of the electricity consumption from the companies. The input data of the usage stage incorporated additional materials, electricity, fuel consumptions and transportation in Australia. Lastly, the input data for the End of Life involved the transportation and disposal process.

At the present time, no single Life Cycle Inventory database can accommodate all 46 raw materials which came from ten specific countries, various manufacturing processes, electricity and transportation as shown in Table 2.3. Therefore, certain libraries from the SimaPro software were carefully selected using the following approach. As this project is an Australian project, therefore the Australian data 2007 library was selected as it represented the Australian situations of the materials, manufacturing process, electricity, transportation and disposal process. This library is the only available Australian database which was developed on the basis of several data sources such as company data, modified from existing European databases and literature reviews from related Australian publications.

For the raw materials from overseas, most of the available databases are based on European data. The IDEMAT2001 database is also based on European database but it focuses highly on the material production. It is the only library that provides the majority of the core raw materials in this project such as fibreglass, carbon fibre, unsaturated polyester resin and styrene. Additionally, the Industry data 2.0 database was selectively included for one product as it provides a specific raw material which was not available in the IDEMAT2001 database. Furthermore, among those 46 materials a number of them are specific chemicals which are not available in any database. Therefore, the generic organic chemicals and inorganic chemicals of the ETH-ESU 96 database were used to represent all chemicals that are not available in any of the databases.

For the manufacturing process in Australia, most of the input data from the companies were obtained as the amount of electricity consumption. Therefore, the electricity generation as the average and specific states were chosen from the Australia data 2007 database. On the other hand, for the manufacturing process of the traditional products, most processes were also available in the Australia data 2007 database except for the screw production and zinc coating process. Therefore, the Data Archive and the ETU-ESU 96 databases were used to provide such processes.

Additionally, the transportation methods that were involved in this project are the road and water transportation used overseas and in Australia. The Australia data 2007 database was used for the water transportation from overseas to Australia and the road transportation in Australia. For other countries, the Franklin USA 98 database was used for the truck travel in the USA as this database is based on ‘a variety of public and private USA statistical sources, reports, and telephone conversations with experts'[3] []. The ETH-ESU 96 database was selected to represent the truck used in Europe and the Buwal 250 database is a Swiss based database but its 40 tonne truck included the generic Life cycle inventory data of energy. Therefore, it was used to represent the truck used in China.

2.5.1 Data quality and uncertainty

The Life Cycle Assessment by nature is a complex study which deals with various input data and series of data sources. It needs to be noted that the methodology involves a certain level of uncertainty from various sources.

The first uncertainty source may come from the provided input data from the company which were the types and quantities of raw materials, the electricity consumptions and the assumptions for the usage stage. The reason being, that some companies were not able to provide the Material Safety Datasheets or did not specify certain ingredients due to confidentiality reasons or the materials were estimated as the product was not in production. As a result, some chemicals or substances may not be included in the analysis. The electricity consumption calculation was quite straightforward where each company estimated their usage via a different approach. For instance, one company estimated their usage by using the information of the power consumption for their machines in the production line, production time and production rate. Some other company estimated their usage by examining their electricity bill to find the amount of electricity consumed and divided that value by the production volume. Another company may estimate the value from the power consumption in a unit of kilowatt of each involved machine, using estimated production time and production rate. Most assumptions for the usage of their products and the comparable products stage were made by the associate company which may apply only for that particular situation.

The second uncertainty source may come from the Life Cycle Inventory databases which are often established from certain approaches and assumptions. It may either under or overestimate the processes as these processes were developed from either by measuring from the companies, through reviewing literature review and interpolating the data from the analogy process. The selected databases represented the best available databases at the present time. However, as the values represent certain situations over a given period of time, these values are often referred to as an average technology level. Therefore, the produced results may be significantly different from the actual situation. For instance, the electricity is generated differently in different countries as it maybe produced from various combinations of energy sources such as coal, oil, natural gas, nuclear power and hydropower. Therefore, as a reliable database for those

[3] PRe consultants BV, "SimaPro," 7 ed. The Netherlands, 2006.

particular ten countries was not available in a comparable database, the European databases were used to represent those countries. Moreover, the transportation during the production was also applied for a particular process which may not represent the real practice. Nevertheless, a further attempt was made by attempting to modify the existing database with the relevant energy source. For instance, the screw production database was based on the electricity consumption in one European country. In this case the electricity process was substituted with the Australia data 2007 database.

In this regard, a certain weakness of the database is worth noting. In terms of the time period these databases base their values on, a number of processes from the IDEMAT2001, ETH-ESU 96 and Buwal250 databases were referred back to 1990 to 1994 and the most current process represent 2004. The Industry data 2.0 database was based on the years 2000-2004. The Franklin USA 98 database was based on 1995 to 1999 and the Australian data 2007 database[4] was based on 1980 to 2009. Most databases referred their technology level as an average and provided the standard Life Cycle Inventory data which were the amount of raw materials, resource, electricity, transportation, infrastructure and emissions. For example, a kilogram of fibreglass uses 0.56 kg of sand, consumes 0.15 of natural gas, using 0.37 MJ of electricity and emits 0.42 kg of CO_2. However, a certain process may only contain electricity or energy resource such as the production of screws and the related cold transforming process.

The third uncertainty source may come from the Life Cycle Impact Assessment methods as these methods were developed based on certain scopes and certain calculation approaches that may include and exclude certain aspects. For instance, wood was not included in the Cumulative Energy Demand 1.04 analysis, the IPCC GWP 1.0 does not 'account for radiative forcing due to emissions of NOx, water, sulphate, etc.' and the Eco-Indicator 99 H/A 1.03 method is based on a certain model. Therefore, these methods can be considered as an estimation but are not the exact value. Nonetheless, these methods were selected as the available best methods and the most widely used for calculating the embodied energy and its environmental impacts. In practice, if the same method is applied in two different product designs, the results can be used as an indication of their environmental performance.

In summary, the uncertainties may come from various sources such as the input data from the companies, the Life Cycle Inventory databases and the Life Cycle Impact Assessment methods due to the nature of the Life Cycle Assessment method. Nevertheless, each input data, database and the methods were selected carefully and were the best data sources available at the present time.

The embodied energy of these processes were analysed and validated with other literature reviews. It was found that the selected databases were within the reported ranges of those literature reviews. Moreover, it was revealed that the deviation of the embodied energy from one analysis to another is quite normal as it is depends on the system boundary and the input data. The large variation was found in the

[4] The database background is provided in Appendix C.

high embodied energy materials or materials which involve different chemicals such as plastics. For example nylon was reported to vary from 160 to 365 MJ per kg whilst fibreglass can vary from 2.56 to 62 MJ per kg.

Overall, the results of this project may be classified as in the lower bound of the actual embodied energy value. This is due to those mentioned uncertainties and also the fact that certain input data such as some specific chemicals were either omitted or assumed as general organic or inorganic chemicals as they were not available in the current databases.

2.6 Input-Output Model

The input-output model of the cradle-to-factory analysis is developed in a spreadsheet format as shown in the block diagram in Figure 2.7 where each block shows the results which are expressed as MJ_{eq}, kg CO_{2eq} and points. An example of the spreadsheet model for the cradle-to-factory analysis is illustrated in Figure 2.8. The input data can be altered by entering different quantities of kilogram and kilometre at the blue font cells where an arrow sign is present. The technical manual is provided in Appendix B.

Consequently, the input-output model of the cradle-to-grave and an example of its spreadsheet model are demonstrated in Figures 2.9 and 2.10 respectively. Similarly, the cradle-to-grave results are expressed as MJ_{eq}, kg CO_{2eq} and points for each process or activity across the product life cycle stages as demonstrated in Figure 2.10. The model also provides the results in both tabulated and graphical formats. Figures 2.11 and 2.12 demonstrate examples of the stated results.

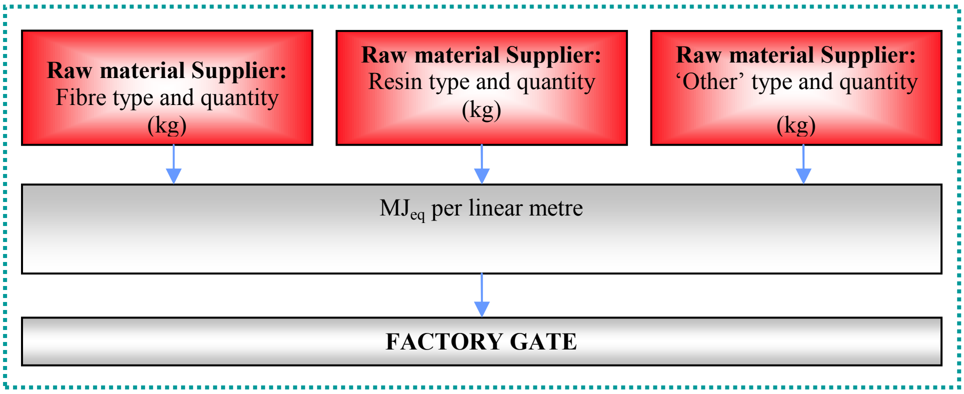


Figure 2.7: Block diagram of the cradle-to-factory analysis

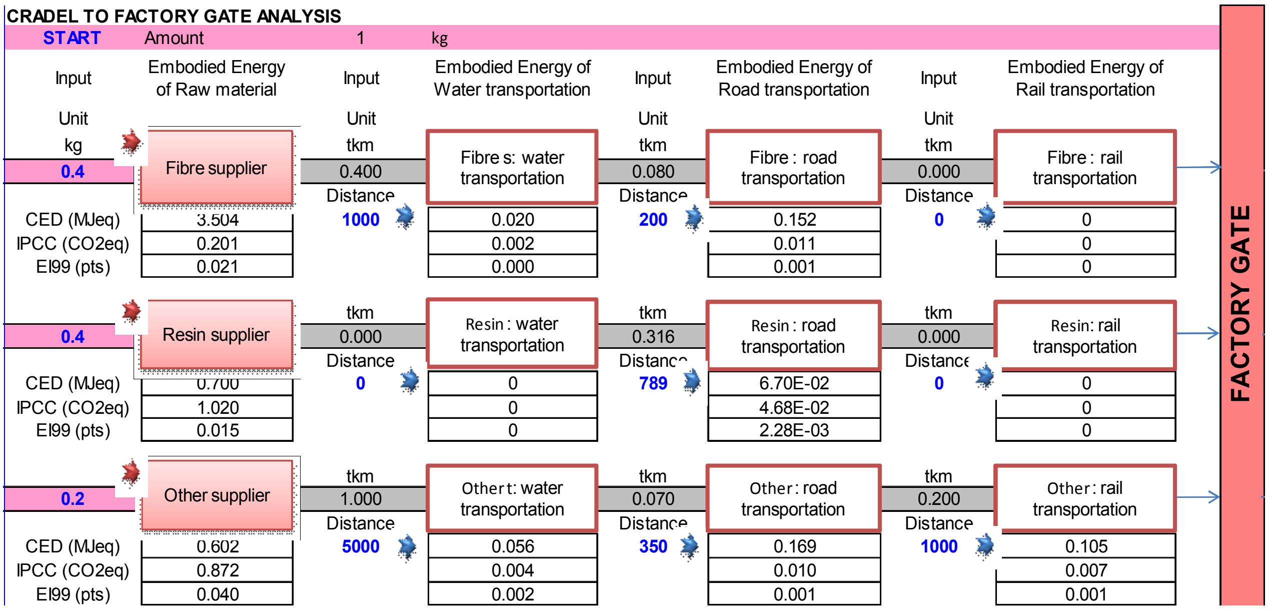


Figure 2.8: Spreadsheet model example of the cradle-to-factory analysis

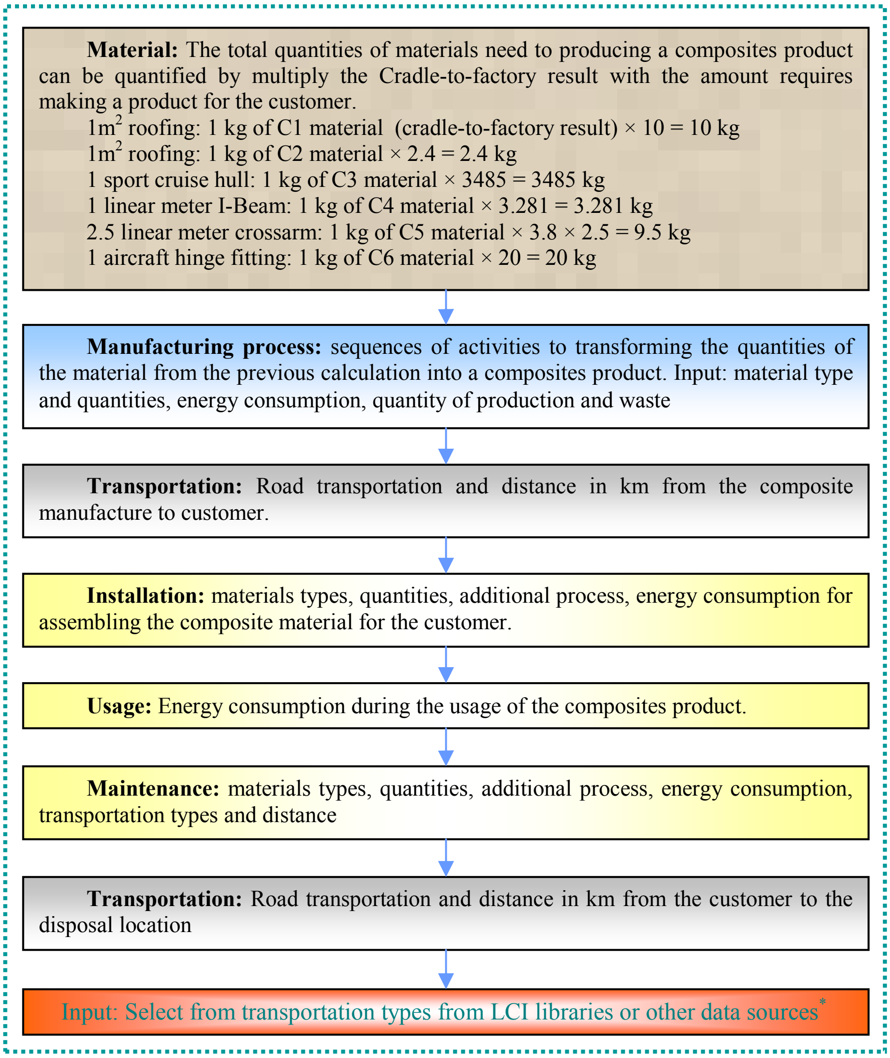


Figure 2.9: Block diagram of the cradle-to-grave analysis

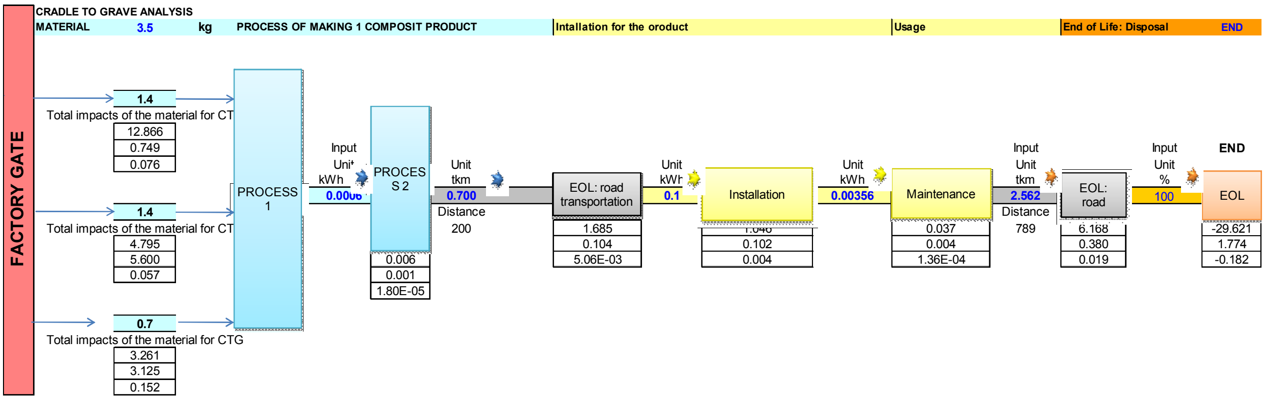


Figure 2.10: Spreadsheet model example of the cradle-to-grave analysis

Cradle to factory gate	Table of the input data from the model	Report: Results from the input data from the model			Report: Product life cycle stages result			Report: Results from the input data from the model					
	Input: Amount per 1 kg of composites material	CED 1.04 (MJeq)	IPCC 1.00 (kg of CO2eq)	EI99 2.03 (points)	CED 1.04 (MJeq)	IPCC 1.00 (kg of CO2eq)	EI99 2.03 (points)	CO (kg)	CO2 (kg)	NO2 (kg)	SO2 (kg)	Partibulate (unspecified) kg	VOC (kg)
Extraction energy	0.4	3.504E+00	2.010E-01	2.100E-02	4.806E+00	2.093E+00	7.600E-02	4.027E-01	6.950E-05	1.598E-03	1.869E-03	3.205E-04	0.000E+00
	0.4	7.000E-01	1.020E+00	1.500E-02				1.320E+00	2.156E-04	2.444E-03	5.462E-03	1.771E-03	0.000E+00
	0.2	6.020E-01	8.720E-01	4.000E-02				9.495E-01	2.430E-04	1.430E-03	3.544E-03	1.046E-03	6.873E-04
Transportation: Suppliers to Company	0.400	2.000E-02	2.000E-03	2.399E-04	1.803E-01	1.352E-02	7.898E-04	2.063E-03	2.667E-06	-2.271E-21	2.372E-06	2.422E-10	4.282E-15
	0.08	1.520E-01	1.100E-02	5.000E-04				1.133E-02	4.598E-05	2.568E-21	9.034E-06	1.336E-09	2.362E-14
	0.078	7.305E-03	4.605E-04	4.699E-05				4.042E-04	5.224E-07	-4.577E-22	4.647E-07	4.744E-11	8.389E-16
	0.0004	9.631E-04	5.925E-05	2.890E-06				5.664E-05	2.299E-07	1.284E-23	4.517E-08	6.679E-12	1.181E-16
Total CTF	1	4.986E+00	2.107E+00	7.679E-02	4.986E+00	2.107E+00	7.679E-02	2.686E+00	5.775E-04	5.473E-03	1.089E-02	3.137E-03	6.873E-04
Material	3.5	4.986E+01	2.107E+01	7.679E-01	4.986E+01	2.107E+01	7.679E-01	3.815E+00	7.216E-04	9.151E-03	1.610E-02	4.433E-03	1.203E-04
Process	0.0006	6.141E-03	5.949E-04	1.799E-05	7.165E-03	6.940E-04	2.098E-05	2.129E-07	6.820E-06	-3.455E-23	4.213E-07	1.131E-08	2.001E-13
	0.0001	1.024E-03	9.914E-05	2.998E-06				3.548E-08	1.137E-06	-5.758E-24	7.021E-08	1.886E-09	3.335E-14
Usage	2.75	7.345E+01	5.823E+00	6.549E-01	7.616E+01	6.058E+00	6.724E-01	2.106E-01	4.634E+00	6.579E-18	8.650E-03	1.314E-01	1.799E-06
	0.06	2.716E+00	2.349E-01	1.755E-02				4.632E-03	1.024E-01	2.658E-19	2.651E-04	2.868E-03	3.929E-08
EOL	2.562	6.168E+00	3.795E-01	1.851E-02	-2.345E+01	2.154E+00	-1.636E-01	1.472E-03	3.628E-01	-9.229E-19	2.893E-04	1.088E-10	7.566E-13
	100	-2.962E+01	1.774E+00	-1.821E-01				-1.225E-01	-1.030E+00	-1.445E-15	-4.891E-03	-1.916E-08	-1.892E-06
Total CTG	Total	1.026E+02	2.928E+01	1.277E+00	1.026E+02	2.928E+01	1.277E+00	3.909E+00	4.070E+00	9.151E-03	2.041E-02	1.387E-01	1.202E-04

Figure 2.11: Example of embodied energy results generated as a tabulated format from the spreadsheet model

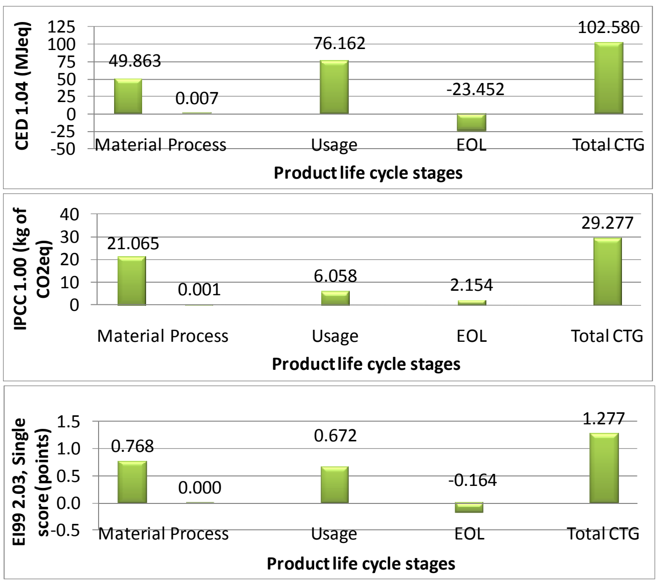


Figure 2.12: Example of embodied energy results generated from the spreadsheet model

2.7 Conclusion

This chapter presents the methodology of the embodied energy analysis. In the first section of this chapter, a background of the Life Cycle Assessment method was provided as this method is used predominantly in this study.

Subsequently, the Life Cycle Impact Assessment methods, namely the Cumulative Energy Demand, IPCC2007 GWP100a and Eco-Indicator-99 H/A (EI99) methods were discussed. These three methods were selected as a tool to calculate the embodied energy for the cradle-to-factory and the cradle-to-grave analyses.

The second section described the embodied energy analysis methodology as a whole. The approach to collect input data for the cradle-to-factory and the cradle-to-grave analyses was discussed in the later section. Consequently, the input data was summarised in a tabulated form, as data collection is an important activity for this analysis. An emphasis was made to clarify how and which data was collected for the two analyses.

Lastly, the material and energy flow model was shown to demonstrate the input-output model for the cradle-to-factory and the cradle-to-grave analyses. An example of the input-output model is also demonstrated as a spreadsheet model.

The embodied energy of the six composite products were analysed using the methodology as stated in this chapter. The next six chapters illustrate the embodied energy results for six composite products and their comparable products.

CHAPTER3 B-PODS PTY LTD (TRACTILE) -EMBODIED ENERGY OF ROOF TILE

3.1 Introduction

Traditionally, roof tiles are made from conventional metals such as coated steel sheet or concrete. This is due to the fact that they have the required physical properties such as strength, durability and low maintenance.

Alternatively, B-Pods Pty Ltd (Tractile) has developed the patented Tractile™ system which designed roof tiles, roof batons, ridge cap tiles, hip tiles and barges. The roof tiles of B-Pods Pty Ltd will be manufactured from glass reinforced plastic. The material has similar properties to that of a roof tile made from coated steel sheet or concrete. However, it differs in that it is more durable, easier to install and has lower maintenance. The composite roof tile is fabricated using the sheet moulding compound process which allows the tile to be formed into different shapes as shown in Figure 3.1. The installation of this composite roof tile is simple and quick which requires fewer batons and results in a lower labour cost as shown in Figure 3.2[5].

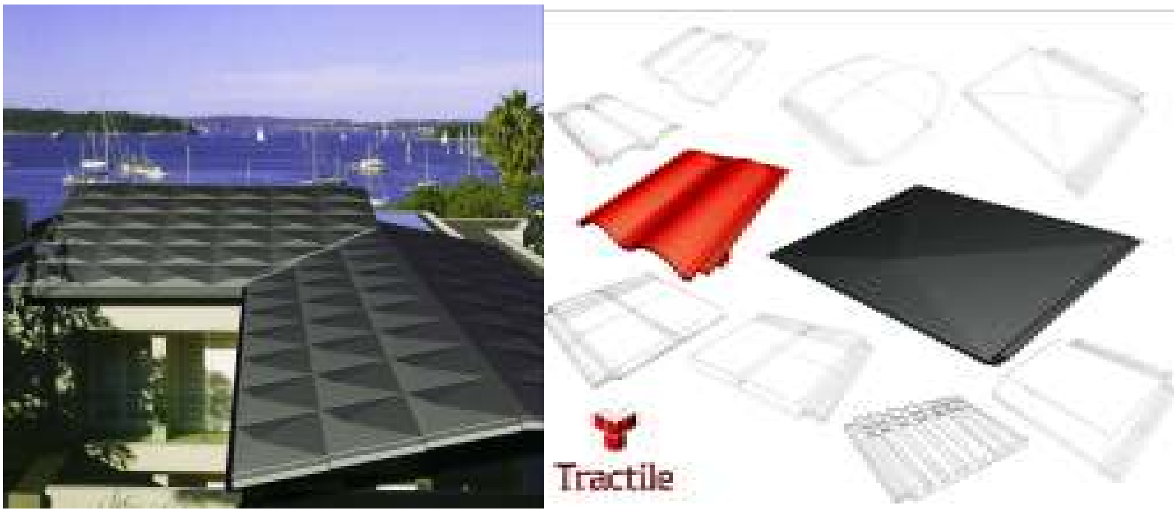


Figure 3.1: Composite roof tile*

[5] www.tractile.com.au

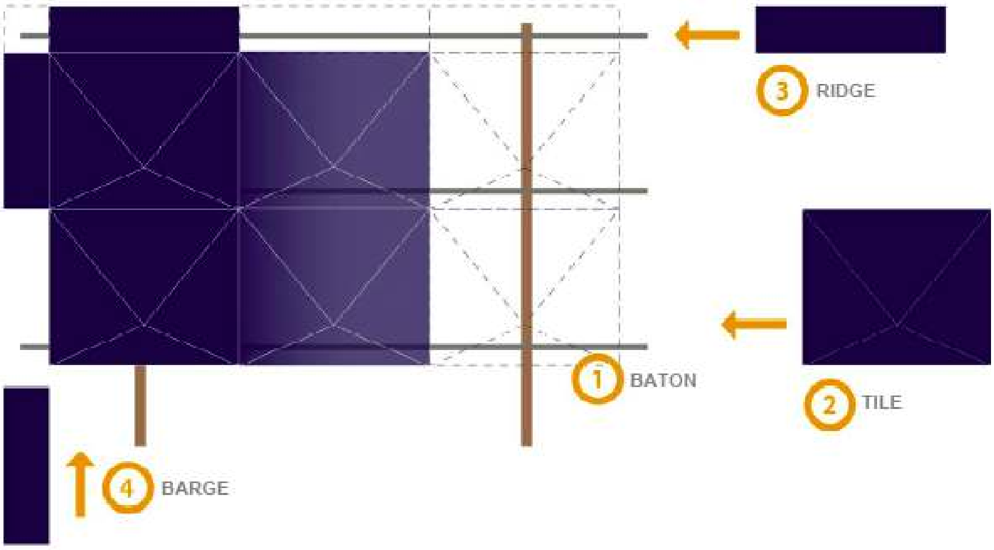


Figure 3.2: Installation system of the Tractile roof tile

Generally, the composite roof tile does have some physical and economical advantages over ones made from traditional materials. In terms of their environmental performance, it is not so clear and therefore this project aimed to investigate the embodied energy of the Tractile roof tile that was designed by B-Pods Pty Ltd.

Therefore, this chapter aims to assess the embodied energy and the environmental impact of the raw materials that are used to make a kilogram of glass reinforced plastic designed by B-Pods Pty Ltd. The embodied energy analysis is used to compare a square metre of roof tile made from three different materials, namely Tractile roof tile, concrete tile and coated steel sheet. Life Cycle Assessment is used as a tool to calculate the embodied energy and the total environmental impact of a kilogram of glass reinforced plastic and those three different roof tile materials.

Cradle-to-factory[6] analysis is used in this chapter to determine the embodied energy and the total environmental impacts of the raw materials required to make a kilogram of the glass reinforced plastic. This material is designed by B-Pods Pty Ltd to be used as a material for the production of the Tractile™ system.

---

[6] Technically, the cradle-to-factory (gate) analysis is commonly defined as "an assessment of a partial product life cycle from manufacture ('cradle') to the factory gate before it is transported to the consumer" (Reference: Moreno, A., 2008, The DEPUIS HANDBOOK Chapter 4: Methodology of Life Cycle Assessment, Accessed: October 2009, http://www.depuis.enea.it/dvd/website.html). However, cradle-to-factory analysis in this project is specified as the embodied energy incurred during the raw material extraction and the transportation from suppliers to manufacturers.

In addition, cradle-to-grave analysis is employed to compare the embodied energy of the life cycle for a square metre of roof tile, which is made of the Tractile roof tile, concrete tile and steel sheet. Cradle-to-grave analysis is an assessment of a product life cycle including raw material extraction, manufacturing process, usage, transportation and end-of-life.

The outline of this chapter is as follows:

- Methodology overview of the cradle-to-factory and the cradle-to-grave analysis
- General scopes and assumptions of the analyses
- Description of a kilogram of the raw materials for making the Tractile roof tile
- Description of one square metre of roof tile that is made from the Tractile roof tile, a concrete tile and coated steel sheet.
- Input data of the cradle-to-factory and the cradle-to-grave analyses
- Cradle-to-factory results and discussions: the embodied energy of the raw materials required to make a kilogram of the Tractile roof tile
- Cradle-to-grave results and discussions: the comparison between one square metre of roof tile made from the Tractile roof tile, concrete tile and steel sheet.
- Conclusion is drawn in the last section of the chapter

3.2 Methodology Overview

3.2.1 Embodied energy analysis

In this study, the embodied energy analysis of a roof tile comprises of the cradle-to-factory and the cradle-to-grave analyses as shown in Figure 3.3. These analyses employ the Life Cycle Assessment method to assess the environmental impacts of all life cycle stages as shown in Figure 3.3. The methodology of these two analyses is described briefly as follows.

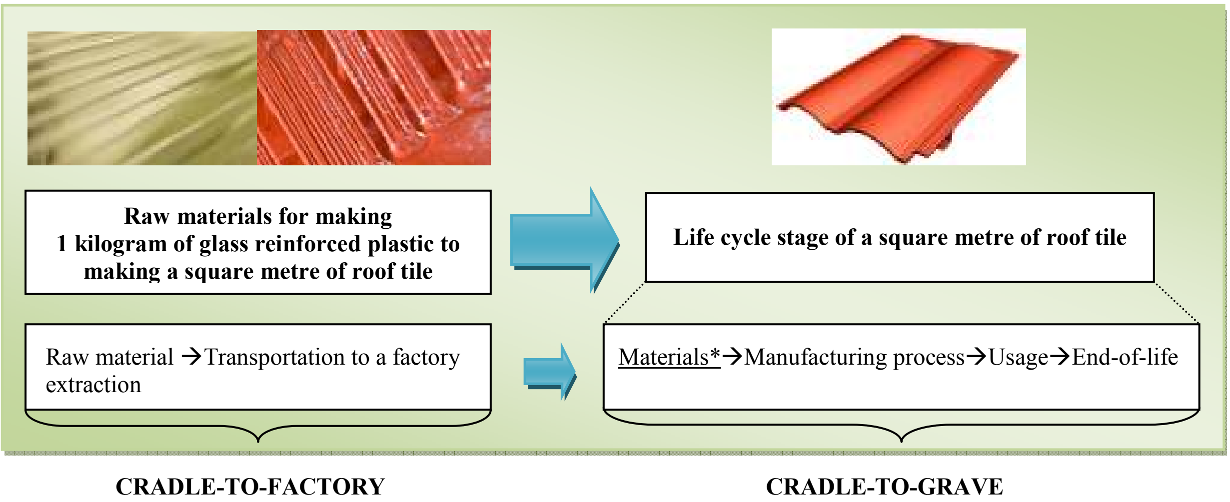


Figure 3.3: Scopes of the cradle-to-factory and the cradle-to-grave analyses[7].

The methodology of these two analyses is described briefly as follows. Firstly, the cradle-to-factory analysis assesses the embodied energy and the total environmental impacts in making a kilogram of the Tractile roof tile as presented in the left portion of Figure 3.3. This analysis focuses on two main embodied energy sources. They are the raw material extraction and the transportation of raw materials from the supplier to a factory, i.e. B-Pods Pty Ltd. The asterisk sign next to the word 'Materials' in Figure 3.3 indicates that the embodied energy result from this analysis will be used as the input data for the materials stage in the next analysis.

Secondly, the cradle-to-grave analysis as shown in Figure 3.3 calculates the life cycle of the Tractile roof tile with a dimension of a square metre. For comparison purposes this analysis technique is also performed on a square metre of roof tile. The life cycle stages of these products are presented on the right hand side of Figure 3.3 where:

- The materials stage is the total raw materials that are used in making the roof tiles;
- The manufacturing process stage comprises the processes involved in making the roof tiles;

[7] The photographs were taken from www.tractile.com.au and www.exelcomposites.com.

– The usage stage consists of the activities that occur after the roof tiles are manufactured i.e. the installation and maintenance activities, until the product is disposed of. In this case, the usage period is 50 years where the distribution, replacement and maintenance activities are considered;

– The end-of-life stage is the disposal scenario which includes the transportation of the roof tiles to the disposal site and the disposal process.

Finally, the embodied energy and the environmental impacts results from the cradle-to-factory analysis are discussed and the hot spots are identified. For this project a hot spot is defined as the raw materials and/or suppliers which have a high contribution to the embodied energy results. The hot spots analysis was conducted in order to make further suggestions in order to minimise or eliminate the identified raw materials and/or suppliers. Subsequently, the embodied energy results from the cradle-to-grave analysis of a square metre of the Tractile roof tile are analysed and compared with the life cycle of a square metre of concrete tile and coated steel sheet.

3.2.2 Scopes and assumptions of the embodied energy analysis

The Table 3.1 and 3.2 are presented in this section to clarify the scopes and assumptions that were produced for the cradle-to-factory and the cradle-to-grave analyses. Table 3.1 provides the main scope of the cradle-to-factory analysis which focuses on quantifying the embodied energy of the raw materials in making a kilogram of the glass reinforced plastic, as well as, the scopes of the input data that are associated with the raw material extraction and their associated transportation. Furthermore, Table 3.1 shows the data sources that are used to make the assumptions for the input data of the cradle-to-factory analysis. Overall, the input data in terms of the quantities and types of materials and transportation are provided by B-Pods Pty Ltd. The rest of the data is assumed using the libraries from the database of the LCA software, SimaPro 7.1.8.

CRADLE-TO-FACTORY				
Scope: To quantify the embodied energy of the raw materials in making 1 kilogram of the Tractile roof tile.				
Input data	Amount of the raw materials used in making 1 kilogram of the Tractile roof tile.			
Material life cycle stage	**Scopes and assumptions**	**Data sources** BT	AU	ID
Raw material extraction	Amount of raw materials (kg)	✓		✓
	Material types	✓(LR and MSDs)		✓
Transportation of raw materials: *From:* Suppliers *To:* B-Pods Pty Ltd (Queensland)	The locations of suppliers	✓		
	Distance (km): Measure by using the online maps	✓		
	Transportation types	✓	✓	

Note: B-Pods Pty Ltd (BT), Literature review (LR), Material Safety Datasheets (MSDs), the 'Australia data 2007'(AU) and the 'IDEMAT2001'(ID) libraries are the databases from the SimaPro 7.1.8 software.

Table 3.1: Scopes and assumptions of the cradle-to-factory analysis

CRADLE-TO-GRAVE						
Scope: To analyse the embodied energy for the 1 square metre of roof tiles that are made from the Tractile roof tile, a concrete tile and coated steel sheet over a life span of 50 years.						
Life cycle stages of the Roof tiles	**Scopes and assumptions**	**Data sources**				
		BT	LR	AU	ET	ID
Material stage: *Input data for amount of the raw materials per a square metre of roof tile.*	***Tractile roof tile:***					
	- *Fibre composite:* 10 kg per square metre Multiply the embodied energy results from the cradle-to-factory analysis in the unit of per kg with 10 kg/ square metre	✓	✓	✓	✓	✓
	Concrete roof tile:					
	- *Concrete tile:* 55 kg per square metre	✓	✓	✓		
	Metal and pigment coated steel sheeting:					
	- *Steel sheet 0.42mm BMT:* 4.35 kg per square metre	✓	✓	✓		
Manufacturing process: *Input data*	***Tractile roof tile:***					
	Energy type: Average Australian high voltage electricity					
	- *Fibre composite:* *4.0323 kWh* per square metre	✓		✓		
	Concrete roof tile: *(no data was provided)*	✓	✓			
	Metal and pigment coated steel sheeting:					
	Process type:					
	- *Steel sheet* [c]*: - Energy and electricity for making steel sheet*			✓		
	- weight of coating metals and colour pigment	✓	✓			
Usage: *Input data* Installation: *From:* B-Pods Pty Ltd *To:* A customer Maintenance: Excluded.	**Transportation for installation:** *All roof tiles*					
	Distance: 200km By: Articulated truck	✓		✓		
	Tractile roof tile:					
	- *coated steel battens:* *2.75* kg per square metre	✓		✓		
	- *three screws:* *0.06* kg per square metre	✓		✓		
	- *one minute each for cutting roof tile, cutting coated steel batten and drilling and screwing of three screws* [b]	✓		✓		
	- *no maintenance required during 50 years warranty*	✓		✓		
	Concrete roof tile:					
	- *Timber battens:* 2.28 kg per square metre	✓		✓		
	- *five clips:* *0.021* kg per square metre	✓		✓		
	- *1 minute each for cutting roof tile, cutting timber battens* [a]					
	- *Based on 50 years warranty condition: required inspection by an expert tradesperson every six year: transportation by a car 8 trips per 50 years for 60 km per trip*	✓	✓			
	Metal and pigment coated steel sheeting:					
	- *coated steel battens:* *0.71* kg per square metre	✓				
	- *six screws:* *0.39* kg per square metre	✓				
	- *one minute each for cutting roof sheet, cutting steel battens* [a]	✓				
	- *two minutes for drilling and screwing of six screws* [b]	✓				
	-Based on 25 years warranty condition: one replacement at 25th year (double the coated steel sheet and the screws and include one trip for an installation) and required inspection by an expert tradesperson every 4 months: transportation by a car, 3 trips per year during 50 years, 60 km per trip	✓	✓			
End-of-life: *Input data*	*All roof tiles: from a* customer *to a* disposal site **Distance***: 200km **By***: Articulated truck for freight	✓		✓		
End-of-life: *Input data* Disposal scenarios	**Household waste**: 100% landfill for fibre composite, concrete and timber and 70% recycling for steel	✓ ✓		✓ ✓		

Note: [a] *The data was sugested by another participant company,* [a]*Arbitrary assumption, B-Pods Pty Ltd (BT), Literature review (LR),the 'Australia data 2007'(AU), the 'ETH-ESU 96' (ET), and the 'IDEMAT2001'(ID) libraries are the databases from the SimaPro 7.1.8 software.*

Table 3.2: Scopes and assumptions of the cradle-to-grave analysis

For instance, the input data for the amount of raw material is based on the information from the Material Safety Datasheets (MSDs) which is provided by B-Pods Pty Ltd. The material types are assumed using the Australian Data 2007 (AU) library and the distance of the transportation of raw materials is found using the online maps provided by Google.

Similarly, Table 3.2 presents the scopes of the cradle-to-grave analysis for the life cycle of the three roof tiles and the life cycle input data in terms of the quantities and types. It is worth highlighting the assumption for the material stage of the Tractile roof tile in Table 3.2. The material stage has two embodied energy sources. They are the raw material extraction and the transportation of those materials. In this stage, the embodied energy of the Tractile roof tile is assumed to be calculated directly from the embodied energy results of the cradle-to-factory analysis. The calculation is carried out by multiplying the embodied energy results from the cradle-to-factory analysis with 10 kg per square metre. For instance, the embodied energy result of the raw material extraction from the cradle-to-factory analysis is 11 MJ_{eq} per kg and the weight of the Tractile roof tile is 10 kg per square metre. Therefore, the embodied energy result for the material stage in this cradle-to-grave analysis is:

$$11\ MJ_{eq} \text{ per kg} \times 10 \text{ kg per square metre} = 110\ MJ_{eq} \text{ per square metre}$$

The input data for the materials and maintenance activities during a life span of 50 years for the concrete tile and the coated steel sheet are assumed based on B-Pods Pty Ltd and the literature review as given in Table3.3.

Life cycle stage	Concrete tile	Coated steel sheet
Materials	Cement 24.9% Sand 60% Pigment 7.5% Water (delivered) 7.5%	Steel sheet, 5% recycled/AU U 4.28 kg/m2 Primary aluminium 53.99% of 150 g/m^2 Zinc 44.69% of 150 g/m^2 Silicon 1.3% of 150 g/m^2 Iron 0.02% of 150g/m^2 Pigment 0.07g/m^2
Usage	Screws and clips were assumed to be made of rolled steel with: 'Rolled steel, 10% recycled/AU U' 4.28 kg/m2 Primary aluminium 53.99% of 150 g/m^2 Zinc 44.69% of 150 g/m^2 Silicon 1.3% of 150 g/m^2 Iron 0.02% of 150g/m^2	
Maintenance activities	Warranty: 50 years Replacement: 0 Maintenance: Inspection by an expert tradesperson every 6 years	Warranty: 25 years Replacement: 1 per 50 year Maintenance: Inspection by an expert tradesperson every 4 months

Table 3.3: Assumptions for the concrete tile and the coated steel sheeting

In addition, the transportation input data for the life cycle of the three roof tiles is specified by B-Pods Pty Ltd. For example, to install a roof tile, the transportation distance from B-Pods Pty Ltd to a customer during the usage stage is assumed to be 200 kilometres. The articulated truck is also assumed as the transportation method to dispose of a roof tile at its end-of-life stage. Table 3.4 is given to clarify the scopes and assumptions of the embodied energy calculation tool which is selected for the cradle-to-factory and the cradle-to-grave analyses.

<table>
<tr><th colspan="5">EMBODIED ENERGY CALCULATION TOOL</th></tr>
<tr><th>Embodied Energy Analysis</th><th colspan="4">Scopes and Assumptions</th></tr>
<tr><td>Embodied energy assessment tool</td><td colspan="4">The Life Cycle Impact Assessment methods from the LCA software, SimaPro 7.1.8 software.</td></tr>
<tr><td>Selection of the Life Cycle Impact Assessment methods</td><td colspan="4">The selection of these methods was based on the generic embodied energy analysis which is often based on the input-output model that are used to quantify the primary energy sources and the results are often expressed in MJ and in kg of CO_2 units. In addition, as the two values from the Cumulative energy demand version 1.04 and the IPCC GWP 100a version 1.00 methods only represent the embodied energy in terms of the primary energy consumption and the impacts from climate change respectively, the points value is also given. This value is calculated from a detail Life Cycle Assessment which considers the impacts on human health, ecosystem quality and resource use. The points value is calculated from the Eco-Indicator 99 H/A version 2.03 method.</td></tr>
<tr><th colspan="5">LIFE CYCLE IMPACT ASSESSMENT METHODS</th></tr>
<tr><th rowspan="2">Method</th><th rowspan="2">Calculation Approach and unit</th><th colspan="3">Embodied Energy Results</th></tr>
<tr><th>Cradle-to-factory</th><th>Cradle-to-grave</th><th>Amount of conventional air pollutions</th></tr>
<tr><td>Cumulative energy demand version 1.04</td><td>Calculation: Calculates the embodied energy in terms of the consumption of the primary energy sources such as fossil fuels, minerals, renewable energy.
Unit: MJ_{eq}</td><td>MJ_{eq} per kg</td><td>MJ_{eq} per square metre</td><td rowspan="3">Carbon monoxide (CO)
Carbon dioxide (CO_2)
Nitrogen dioxide (NO_2)
Sulphur dioxide (SO_2)
Unspecified particulate
Volatile organic compounds (VOC)</td></tr>
<tr><td>IPCC GWP 100a version 1.00</td><td>Calculation: Calculates the greenhouse gas emissions which impact on global warming.
Unit: kg CO_{2eq}</td><td>kg CO_{2eq} per kg</td><td>kg CO_{2eq} per square metre</td></tr>
<tr><td>Eco-Indicator 99 H/A version 2.03</td><td>Calculation: calculates the environmental performance indicator as a single score. This is a comprehensive Life Cycle Assessment analysis which considers the human health, ecosystem quality and resource use impacts.
Unit: points of a single score</td><td>points per kg</td><td>points per square metre</td></tr>
</table>

Table 3.4: The scopes and assumptions for the calculation tools and results of the embodied energy

As a result, three Life Cycle Impact Assessment methods based on the SimaPro 7.1.8 software are shown in the table. They are the Cumulative Energy Demand version 1.04, the IPCC GWP 100a version 1.00 and the Eco-Indicator 99 H/A version 2.03 methods. Furthermore, Table 3.4 summarises the calculation approach and the produced results of the three methods for the cradle-to-factory and the cradle-to-grave analyses. These methods generate the embodied energy results for these analyses in the units of MJ_{eq}, kg CO_{2eq} and points per kg as well as in units of MJ_{eq}, kg CO_{2eq} and points per square metre. Therefore, Figure 3.5 provides additional information to aid in how to interpret these results. Additionally, the amount of six conventional air pollutants as listed in Table 3.3 are as the total airbourne substances that are emitted during the cradle-to-factory and the cradle-to-grave analyses.

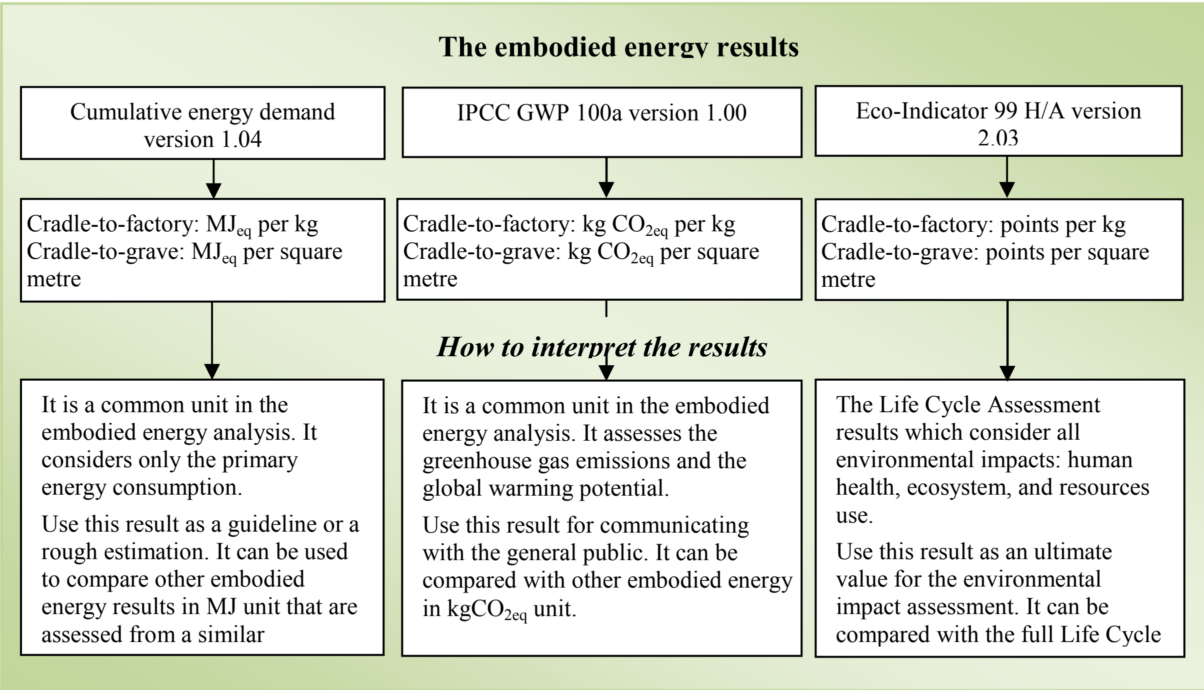


Figure 3.4: How to interpret the embodied energy results

3.3 Material and Product description

3.3.1 Fibre composite description

The description of the raw materials used in manufacturing the fibre composite is summarised in Table 3.5. Various raw materials constitute the composite material such as fibreglass, plastic resins as well as pigment, catalysts and additives. These raw materials are assumed to be supplied by 6 suppliers from the Asia region. The transportation of the raw materials from suppliers to B-Pods Pty Ltd located in Queensland involves road and water transportation. The transportation of the raw materials is presented in the last column of Table 3.5. Additionally, Table 3.5 presents the abbreviations of the raw material type

'M' and its transportation 'M_T' which are provided for later discussion in this chapter. As there are 6 suppliers involved in this analysis, M1 to M6 and also M1_T1 to M6_T2 are presented in Table 3.5.

Raw material type	List of raw material	Region of supplier	Road and water transportation of raw material: from a supplier to the factory, B-Pods Pty Ltd (BPod.)
Fibre glass	M1	Asia	Supplier *(M1) → (M1_T1) → (M1_T2) → Factory, (BPod.)
Resin	M2	Asia	Supplier *(M2) → (M2_T1) → (M2_T2) → Factory, (BPod.)
Others: such as pigment, catalysts, and additives	M3 to M6	Asia	Supplier *(M3 to M6) → (M_T1) → (M_T2) → Factory, (BPod.)

Note: The abbreviations of 'M' and "M_T' are provided for the discussion of Figure 3.8.
Raw material types (M), First transportation of the raw material (M_T1), Second transportation of the raw material (M_T2)
(Road transportation such as a truck) and (Water transportation such as an Australian international shipping)

Table 3.5: Raw materials and the transportation of raw materials in making a kilogram of the fibre composite

3.3.2 A roof tile description

The cradle-to-grave analysis focuses on assessing the embodied energy of 1 square metre of roof tile which is made from three materials comprising:

- 1 square metre of Tractile roof tile, coated steel battens and coated steel screws

  Remarks: At present, the fibre composite roof tile is currently in the conceptual product stage. As a result, the majority of the input data for the cradle-to-grave analysis is based on assumptions provided by B-Pods Pty Ltd. Due to these uncertainties, it should be noted that the cradle-to-grave results may be under or overestimated;

- 1 square metre of concrete roof tile, timber battens and coated steel clips;
- 1 square metre of coated steel sheet, coated steel battens and coated steel screws

General description for the roof tile life cycle is defined as follows:

1. The functional unit of the case study is based on the lifetime of 50 years which is the same as the warranty of the Tractile roof tile;
2. The cradle-to-grave analysis for the 1 square metre of roof tile is made using the provided input data by B-Pods Pty Ltd, including the quantities of the materials and energy consumption for the sheet moulding compound process;

3. The materials as additional components in the cradle-to-grave analysis for a square metre of roof tile are the coated steel or the timber battens and the coated steel screws and clips as the fasteners, which means that the other common components for a roofing system such as the trusses, the reflective foil sarking and thermal insulation materials are excluded due to lack of information from the manufacturer;
4. The usage stage involved the installation process involves the installation transportation, the electricity required in cutting the roof tile and roof sheet, the coated steel and timber battens, also the drilling and screwing processes for the fasteners;
5. The maintenance activities include the replacement and inspection by an expert tradesperson who travels by car over a distance of 60 km. The assumption is made on the basis of B-Pods Pty Ltd and their literature review information;
6. The End-of-Life (EOL) activities include the disposal transportation and process.

3.4 Input Data

The input data of the cradle-to-grave analysis for the three roof tiles made from the Tractile roof tile, concrete tile and coated steel sheet are presented in Tables 3.6 and 3.7 respectively. This input data is derived from the scopes and assumptions in Section 3.2.2. Therefore, the input data of all life cycle stages are presented in terms of a unit, the amount and the 'material/process description' which represents the material and manufacturing process types[8].

[8] In relation to this, the data sources for the input data of 'Material/process description' and 'Amount' are also given in the last column of Tables 3.6 and 3. 7 for the reference of the database background.

Life cycle stage	Materials/Processes description	Unit	Amount	Database
Material	Tractile roof tile	kg	10	Multiply 1kg results from the cradle-to-factory analysis by10
Process	Total electricity consumption for Sheet moulding process	kWh	4.03	Australian data 2007
Usage: Installation	Coated Steel battens	kg	2.75	B-Pod Pty Ltd, literature review and Australian data 2007
	Coated Steel screws	kg	0.06	-Pod Pty Ltd, literature review and Australian data 2007
	Cutting roof tile	kWh	0.02	Australian data 2007
	Cutting steel battens	kWh	0.02	Australian data 2007
	Drilling & screwing; Cordless drill	kWh	0.0058	Australian data 2007
	Articulated truck freight, customisable/AU U: (12.81kg*200km/1000)	tkm	2.56	Australian data 2007
Usage: Maintenance	No maintenance required	-	-	B-Pod Pty Ltd
End-of-life: Disposal transportation	Articulated truck freight, customisable/AU U: (12.81kg*200km/1000)	tkm	2.56	Australian data 2007
End-of-life: Household waste	Household waste: 100% landfill for Fibre composite and 70% for steel recycling	%	100	Australian data 2007

Table 3.6: Input data for a square metre of the Tractile roof tile

Life cycle stage	Materials/Processes description	Unit	Amount	Database
Material	Concrete tile	kg	55	B-Pod Pty Ltd, literature review and Australian data 2007
Process:	Excluding the manufacturing process due to lack of input data	-	-	B-Pod Pty Ltd and literature review
Usage: Installation	Timber battens	kg	2.28	Australian data 2007
	Coated Steel screws	kg	0.021	B-Pod Pty Ltd, literature review and Australian data 2007
	Cutting roof tile	kWh	0.02	Australian data 2007
	Cutting timber battens	kWh	0.02	Australian data 2007
	Articulated truck freight, customisable/AU U: (57.301kg (55+2.28+0.021)*200km/1000)	tkm	11.46	Australian data 2007
Usage: Maintenance	Car average/AU U: Transportation for inspection at year 6, 12, 18, 24, 30, 36, 42 and 48 (8 trips per 50 years)*60km	km	480	B-Pod Pty Ltd, literature review and Australian data 2007
End-of-life: Disposal transportation	Articulated truck freight, customisable/AU U: (57.301kg(55+2.28+0.021)*200km/1000)	tkm	11.46	Australian data 2007
End-of-life: Household waste	Household waste: 100% landfill for concrete and timber as well as 70% for steel recycling	%	100	Australian data 2007

Table 3.7: Input data for a square metre of concrete tile

Life cycle stage	Materials/Processes description	Unit	Amount	Database
Material	Modified steel sheet, 5% recycled/AU U: 2 sets of 4.35kg during 50 years	kg	8.7	B-Pod Pty Ltd, literature review and Australian data 2007
Process	Energy of the modified steel sheet, 5% recycled/AU U	kg	8.7	Australian data 2007
Usage: Installation	Coated Steel battens: modified rolled steel, 10% recycled/AU U: 1 set during 50 years (no replacement)	kg	0.71	B-Pod Pty Ltd, literature review and Australian data 2007
	Coated Steel screws: modified rolled steel, 10% recycled/AU U: 2 sets of 0.39 kg during 50 years	kg	0.78	-Pod Pty Ltd, literature review and Australian data 2007
	Cutting roof sheet for 2 sets: Assumed: cutting 2m takes (1mins/60)h*1.2kw	kWh	0.04	Australian data 2007
	Cutting steel battens (no replacement)	kWh	0.02	Australian data 2007
	2 sets of Drilling & screwing; Cordless drill: (2min/60)h*0.35kw*2	kWh	0.02	Australian data 2007
	Articulated truck freight, customisable/AU U: at 1st year (4.35+0.71+0.39)	tkm	1.09	Australian data 2007
Usage: Maintenance	Articulated truck freight, customisable/AU U: at 25th year (4.35+0.39)	tkm	0.948	Australian data 2007
	Car average/AU U: Transportation for inspection (3 trips/year*50 years)*60km	km	9000	B-Pod Pty Ltd, literature review and Australian data 2007
End-of-life: Disposal transportation	Articulated truck freight, customisable/AU U: (4.35+0.71+0.39)	tkm	1.09	Australian data 2007
End-of-life: Household waste	Household waste: 100% landfill for Fibre composite and 70% for steel recycling	%	100	Australian data 2007

Table 3.8: Input data for a square metre of coated steel sheeting.

3.5 Embodied Energy Results

3.5.1 Cradle-to-factory Results and Discussion

The cradle-to-factory analysis used the Life Cycle Assessment method to assess the embodied energy of the raw materials that are comprised in a kilogram of the fibre composite as presented in Figure 3.5. This assessment produced the embodied energy results of primary energy consumption and the greenhouse gas emissions. The total environmental impacts or a single score was also given as a detail Life Cycle AssessmentThese results are expressed in a unit of MJ_{eq} per kg, CO_{2eq} per kg and points per kg respectively.

The total results of these two embodied energy sources are also provided in the last bar of Figures 3.6 (a) to (c). On the whole, the raw materials for a kilogram of fibre composite gave total embodied energy results of 11.23 MJ_{eq}, 1.11 kg CO_{2eq} and 0.05 points.

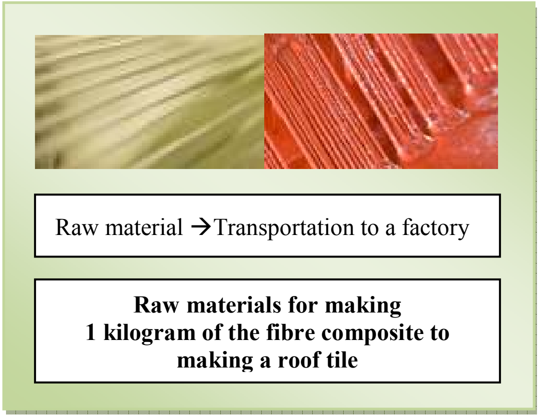


Figure 3.5: Two main embodied energy sources of the cradle-to-factory analysis

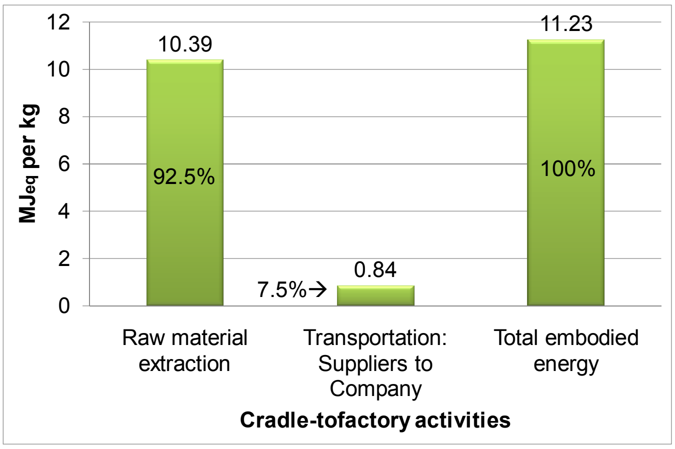
These charts demonstrate the results in terms of the raw material extraction and the transportation of the raw materials from suppliers to B-Pods Pty Ltd. The last bar of the charts shows the total results of the two main embodied energy sources which are the sum of the raw material extraction and the transportation of the raw materials. 80% to 39% of these results consist of the raw material extraction and 4.5% to 20% from the transportation of the raw materials as labelled in Figure 3.6. The distinct contributions of the two embodied energy sources are clearly revealed. The findings suggest that the embodied energy of the fibre composite can be reduced in two different directions.

The first direction is to reduce the high embodied energy of the raw material extraction by using alternative raw materials with a lower embodied energy. The second direction is to be selective in choosing the suppliers in order to ensure low embodied energy in their delivery transportation.

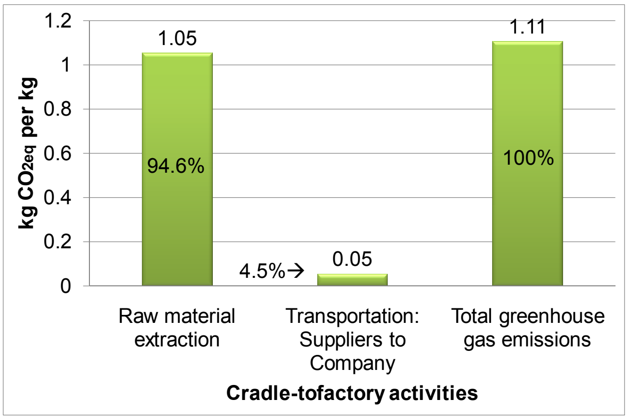
Ideally, the first direction would be the best option as it can reduce the embodied energy dramatically by changing some of the raw materials as the raw material extraction actually contributes a large portion in the total embodied energy result. However, it requires further research and development in finding an alternative or a new raw material which requires further investment of the supporting systems. Therefore, this direction can only be targeted as a long term product development plan.

In practice, the second direction would be more attractive as it is a fast and simple approach which requires only a careful consideration in selecting the suppliers. For instance, the selected suppliers should supply the raw materials that are manufactured locally or require less energy-intensive transportation systems for transporting the raw materials.

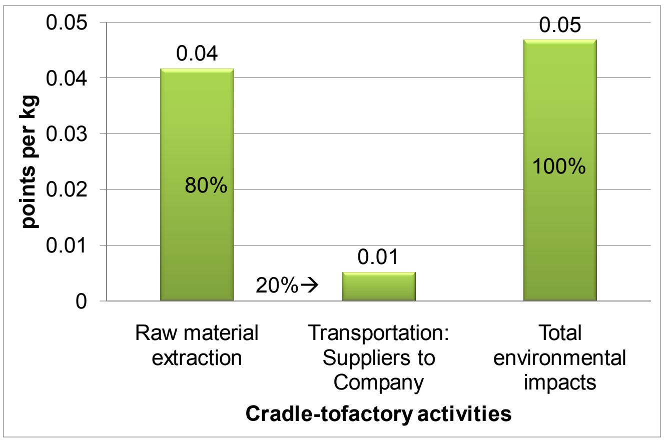
To enhance the implementation of these suggestions, Figure 3.7 explicitly presents the embodied energy for each raw material and its corresponding transportation method. These results are produced from the detailed input data such as the MSDs and the actual location of the suppliers for all raw materials provided by B-Pods Pty Ltd.



(a) Primary energy consumption results in a unit of MJ_{eq}

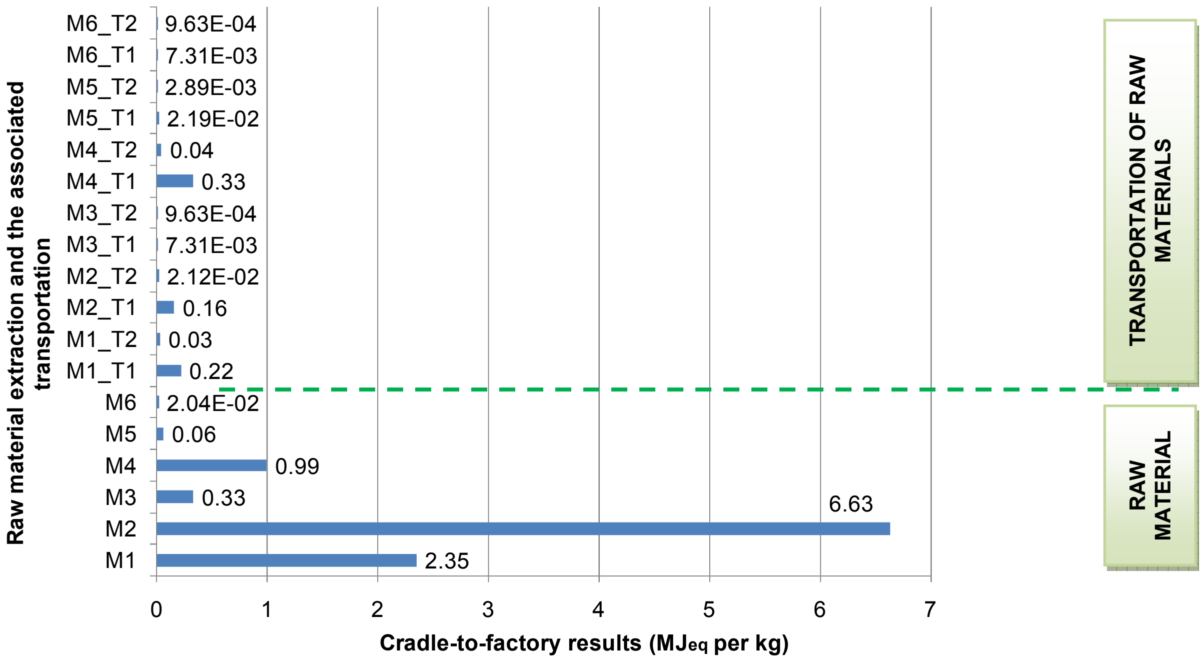


(b) Greenhouse gas emissions in a unit of kg CO_{2eq}



(c) Total environmental impact in a unit of points

Figure 3.6: The cradle-to-factory results for the Tractile roof tile of B-Pods Pty Ltd.



Note:Raw material types (M), First transportation of the raw material (M_T1) and Second transportation of the raw material (M_T2)

Figure 3.7: Detailed embodied energy results (MJ_{eq} per kg) of Tractile roof tile for all raw materials and the associated transportation.

Figure 3.7 reveals that the embodied energy of the fibre composite from B-Pods Pty Ltd is dominated by the combination of several raw materials which originated from overseas suppliers. As a result, a number of hot spots which are the raw materials or the suppliers that have significantly high values are revealed in Figure 3.7.

On this occasion, the raw material (M2) contributes the most followed by the raw material (M1) and (M4) whereby the obvious hot spots of the supplier's transportation are the transportation of the raw materials (M4), (M1) and (M2). Similarly, these higher contributions of the embodied energy for the transportation methods were observed with notable reasons. Since these raw materials were required in high quantities, they needed to be imported from overseas. Therefore, a combination of transportation types is utilized at the same time.

Consequently, these hot spots can be minimised and eliminated by approaching the following recommendations:

- Change the raw material (M2), (M1) and (M4) to alternative materials which have lower embodied energy in their raw material extraction;
- Change the suppliers of the raw material (M4), (M1) and (M2) to local manufacturers;
- Improve the transportation system by avoiding the use of road transportation over a long distance;
- Change the transportation types by leaning more towards water and rail transportation.

3.5.2 Cradle-to-grave Results and Discussion

As in the cradle-to-grave analysis, the Life Cycle Assessment method is used to assess the embodied energy of the whole life cycle of a square metre of Tractile roof tile, concrete tile and coated steel sheet as shown in Figure 3.8. This assessment produces the embodied energy results from three different environmental aspects, which are the primary energy consumption, the greenhouse gas emissions and the total environmental impacts. These results are expressed in a unit of MJ_{eq} per square metre, kg CO_{2eq} per square metre and points per square metre respectively.

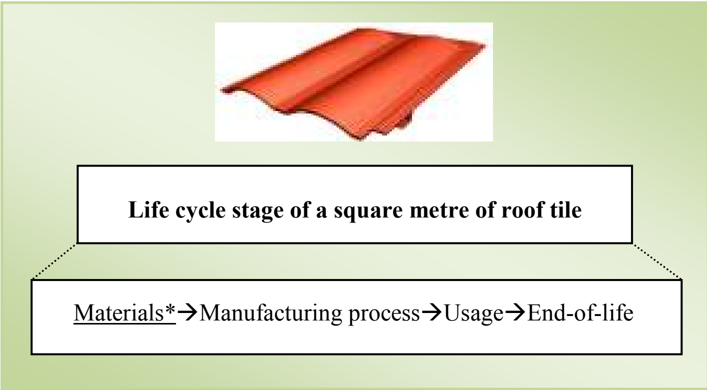


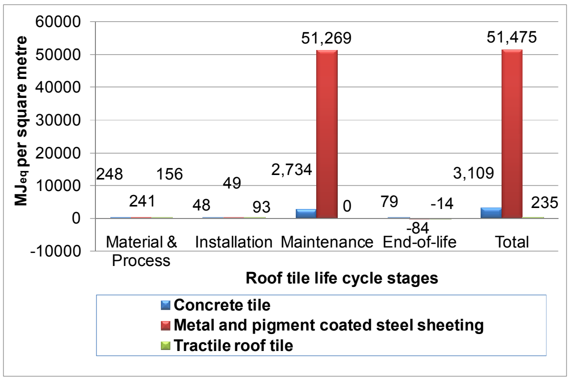
Figure 3.8: The life cycle stages of a square metre of roof tile.

In this section, the three results of all roof tiles are presented in the bar charts in Figures 3.5 to 3.8. Each figure provides two bar charts which represent the embodied energy results for with and without the maintenance processes[9] during its life span of 50 years. These charts show the results in terms of the life cycle stages which are the materials and manufacturing process, installation, maintenance and end-of-life stages as illustrated in Figure 3.5.[10] The installation and maintenance represent the usage stage of the product life cycle. The last bar of the charts gives the total result of the three roof tiles which are the sum of all life cycle stages. The blue bar represents the concrete tile, the red bar shows the metal and pigment coated steel sheeting and the green bar illustrates the Tractile roof tile.

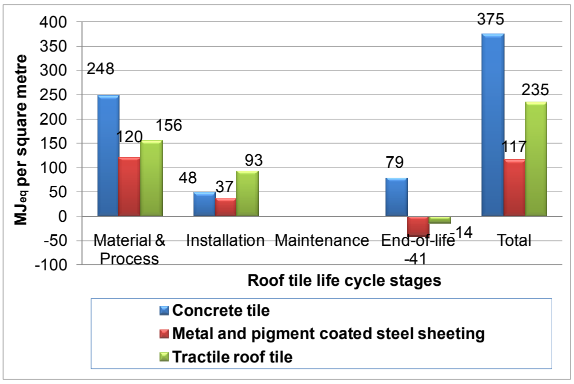
[9] The maintenance bar represents the 60 kilometre fuel consumption of a car which is used by an expert tradesperson for the inspection schedule over a 50 year life span. The inspection activities for the concrete tile were assumed to be inspected every six years while the coated steel sheet should be inspected every four months. Moreover, the replacement and reinstallation at the 25th year was also assumed for the coated steel sheet and its screws which was based on its 25 year warranty. For the Tractile roof tile, it requires no maintenance. These assumptions were based on the literature review of the warranty period and conditions provided from B-Pods Pty Ltd

[10] Noticeably, the materials and manufacturing process are presented as a single bar. This is due to the input data of concrete tile contains only the raw materials as stated from the Material Safety Datasheet (MSDs). Whereas, the metal and pigment coated steel sheeting data were based on the rolled steel from the Australian data 2007 database and additional quantities of metals used for the coating layer as stated in its MSDs.

Figure 3.9 (a) and (b) present the embodied energy results from the environmental aspect of the primary energy consumption which is assessed by the Cumulative Energy Demand version 1.04 (CED1.04) method as introduced in Section 3.2.2. Figure 3.9 (a) illustrates the embodied energy results for the inclusion of the maintenance activities based on the warranty conditions of the product during a 50 year life span.



(a)



(b)

Figure 3.9: Comparison of primary energy consumption results for a square metre of three roofing.

In Regards to Figure 3.9 (b), the results of the maintenance inclusion reveal that the embodied energy of the roof tile at the material and manufacturing process life cycle stage are 248 and 241 MJ_{eq} per square metre for the concrete tile and the metal and pigment coated steel sheeting respectively. The Tractile roof tile has relatively lower embodied energy at 156 MJ_{eq} per square metre. The difference between the Tractile roof tile and the two traditional roofing materials which are the concrete tile and coated steel sheeting equate to 37% and 35% respectively. The reason for this, is due to the fact that a relatively high amount of energy is required during the cement extraction process whereby a second set of steel sheet and screws are assumed to be replaced at the 25th year due to the 25 year warranty limitation. On the other hand, if the maintenance activities are excluded from the life cycle as presented in Figure 3.9 (b) the coated steel sheeting will be less than Tractile by 23%. This is due to the fact that although the coated steel sheeting uses relative high energy for its extraction process but during the application of a square metre it uses less material than the Tractile roof tile.[11]

For the installation activity, the Tractile roof tile is higher than the two traditional roofing materials due to the higher quantity of steel battens which are used during the installation. Nevertheless, the intrinsic difference is the fuel consumption during the installation where the Tractile roof tile uses 6 MJ_{eq} but the

---

[11] Tractile roof tile weight is 10 kg per square metre and the coated steel sheeting weighs 4.35 kg per square metre.

concrete tile consumes 28 MJ_{eq}. This indicates that the Tractile roof tile saves up to 79% of the fuel consumption from the installation transportation compared to the concrete tile.

Another main advantage of the Tractile roof tile is found at the maintenance activities where it consumes zero embodied energy as there is no maintenance required. The coated steel sheeting and the concrete roof tile on the other hand may require intensive transportation from the inspection requirements of the warranty. For the inspection of every 4 months during the 50 years, the metal and pigment coated steel sheeting would consumes 51,269 MJ_{eq} from the fuel consumption of the associated transportation. For the inspection requirement of every six years during the 50 years of the concrete tile, it would consume 2,734 MJ_{eq}.

However, the end-of-life or the disposal life cycle stage of the metal coated steel sheeting performs better than the Tractile roof tile and concrete tile. This is because an assumption is made that 70% of the steel could be recycled[12], whereas the Tractile roof tile, concrete tile and timber were assumed as 100% landfill[13]. Therefore, the embodied energy of the galvanised steel roof sheet at this stage is -84 MJ_{eq} for the maintenance inclusion sceranios and -41 MJ_{eq} for the no maintenance scenarios. This indicates that energy is saved from the recycling process by 84 and 41 MJ_{eq} respectively[14]. Nonetheless, at this stage the Tractile roof tile performs significantly better than the concrete tile as it requires higher quantity than the Tractile roof tile for a square metre roofing application. In this case, the concrete roof tile uses 55 kg per square metre where as the Tractile tile used only 10 kg per square metre. Therefore, the concrete tile gains an embodied energy value of 79 MJ_{eq} from the landfill process and the associated transportation whereas the Tractile roof tile has -14 MJ_{eq}. This negative result indicates that energy is gained back from the recycling process by 14 MJ_{eq} from the 70% recycling for the steel battens and steel screws.

Overall, the total embodied energy results for the life cycle of the concrete tile and the coated steel sheeting are 51,475 and 3,109 MJ_{eq} per square metre respectively for the maintenance scenario. Figure 3.9 (a) shows that the embodied energy for the life cycle of a square metre of a Tractile tile for the maintenance inclusion scenario can be significantly reduced by 92 % and 99.5% when it is fabricated from the Tractile roof tile instead of the concrete tile and the metal and pigment coated steel sheeting. This dramatic reduction occurs at the maintenance stage and is due to the embodied energy being 100% higher for the concrete tile and the coated steel sheeting as Tractile requires no maintenance during its warranty of 50 years. Furthermore, for the exclusion of maintenance scenario, the embodied energy of the two

---

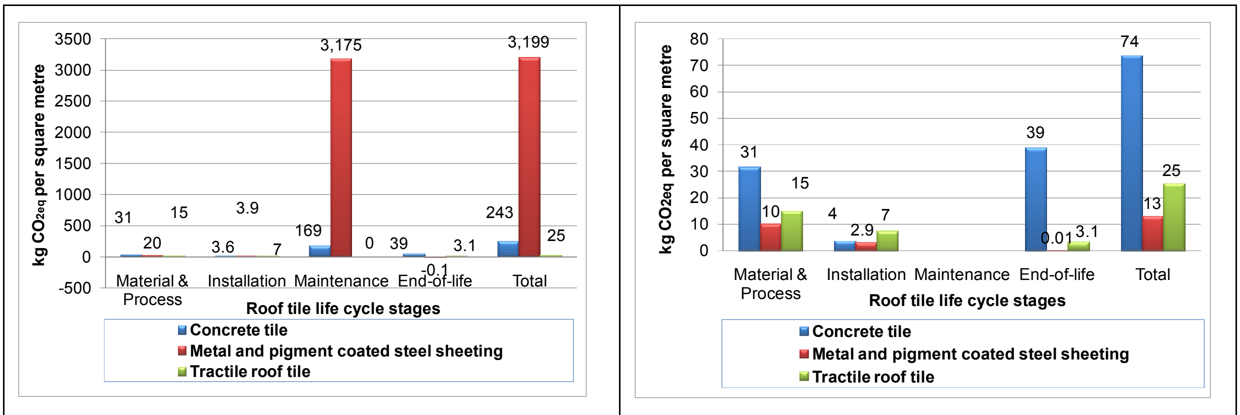
[12] The assumptions were made based on the household waste data from Australian data 2007 library of the Life Cycle Assessment software as shown in Appendix C.

[13] The assumptions were made based on the provided input data from B-Pod Pty Ltd.

[14] The maintenance scenario has a higher embodied energy value due to the calculation being based on two sets of coated steel sheeting.

traditional roofing materials is 375 and 117 MJ_{eq} per square metre respectively. The embodied energy of Tractile is 235 MJ_{eq} for both scenarios as it requires no maintenance inspection during the usage of 50 years. In this case, Figure 3.9 (b) illustrates that Tractile performs better than a concrete tile by 37% but it has a higher embodied energy than the coated steel metal by 50%. This is owing to the fact that Tractile requires less material for a square metre of roofing than the concrete tile whereas for the coated steel sheeting case, Tractile uses higher quantities of the raw materials for the application which requires slightly higher fuel consumption and it cannot be recycled.

Figure 3.10 (a) and (b) present the embodied energy results of the greenhouse gas emissions which is assessed by the IPCC GWP 100a version 1.00 (IPCC1.00) method as introduced in Section 3.2.2. Figure 3.10 (a) illustrates the embodied energy results for the inclusion of the maintenance activities which is based on the warranty conditions of the product during a 50 year life span.



(a) (b)

Figure 3.10: Comparison of greenhouse gas emission results for a square metre of the three roof sheeting

The results of the maintenance inclusion reveal that the embodied energy of the roof tile at the material and manufacturing process life cycle stage are 31 and 20 kg CO_{2eq} per square metre for the concrete tile and the metal and pigment coated steel sheeting respectively. The tractile roof tile has relatively lower embodied energy at 15 kg CO_{2eq} per square metre. The difference between the Tractile roof tile and the two traditional roofing materials which are the concrete tile and coated steel sheeting equate to 52% and 25% respectively. The reason is due to the fact that a relatively high amount of energy is required during the cement extraction process whereby a second set of steel sheet and screws were assumed to be replaced at the 25th year due to the 25 year warranty limitation. Moreover, as the timber frame is used for the concrete tile, it needs to be taken into account the number of the carbon sinks required to offset the loss of those trees used in the installation of the concrete tile. Carbon sinks are when trees are planted or existing forests are preserved in order to help remove CO_2 from the atmosphere[15].

On the other hand, if the maintenance activities are excluded from the life cycle as presented in Figure 3.10 (b) the coated steel sheeting will be less than Tractile by 33%. This is due to the fact that although the coated steel sheeting uses relative high energy for its extraction process but during the application of a square metre it uses less material than the Tractile roof tile.[16]

For the installation activity, the Tractile roof tile is higher than the two traditional roofing materials due to the higher quantity of steel battens which are used during the installation. Nevertheless, the intrinsic difference is the fuel consumption during the installation where the Tractile roof tile uses 0.38 kg CO_{2eq} per square metre but the concrete tile consumes 1.7 kg CO_{2eq} per square metre This indicates that the Tractile roof tile saves up to 78% of the fuel consumption from the installation transportation of the concrete tile.

Another main advantage of the Tractile roof tile is found at the maintenance activities where it consumes zero embodied energy as there is no maintenance required. The coated steel sheeting and the concrete roof tile on the other hand may require intensive transportation from the inspection requirements of the warranty. For the inspection of every 4 months during the 50 years, the metal and pigment coated steel sheeting would consumes 3,175 kg CO_{2eq} from the fuel consumption of the associated transportation. For the inspection requirement of every six years during the 50 year life span of the concrete tile, it would consume 169 kg CO_{2eq}.

However, the end-of-life or the disposal life cycle stage of the metal coated steel sheeting performs better than the Tractile roof tile and concrete tile. This is because an assumption is made that 70% of the steel could be recycled[17], whereas the Tractile roof tile, concrete tile and timber are assumed as 100% landfill[18]. Therefore, the embodied energy of the galvanised steel roof sheet at this stage is -0.1 kg CO_{2eq} for the maintenance inclusion scenarios and 0.01 kg CO_{2eq} for the no maintenance scenarios. The negative value indicates that the greenhouse gas emission is reduced from the recycling process by 0.1 kg CO_{2eq}[19].

---

[15] The sawn hardwood is based on the Australia Data 2007 database from the Life Cycle Assessment software, SimaPro 7.1.8 software. For this particular case, it is assumed that 1.14 kg CO_2 sunk per tonne of wood production.

[16] Tractile roof tile weight is 10 kg per square metre and the coated steel sheeting weighs 4.35 kg per square metre.

[17] The assumptions were made based on the household waste data from Australian data 2007 library of the Life Cycle Assessment software as shown in Appendix D.

[18] The assumptions were made based on the provided input data from B-Pod Pty Ltd.

[19] The maintenance scenario has a higher embodied energy value to the calculation being based on two sets of coated steel sheeting.

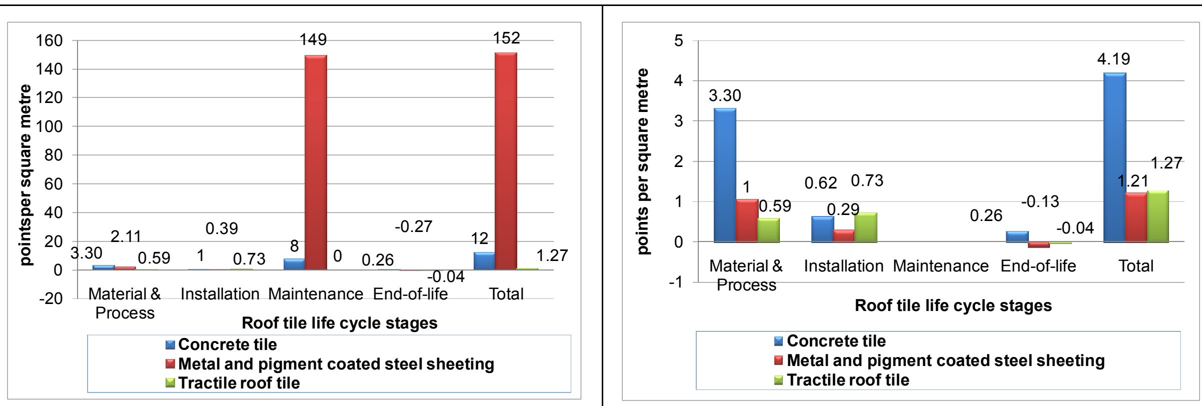
Nonetheless, at this stage the Tractile roof tile performs significantly better than the concrete tile as shown in Figure 3.10 (b). It requires a higher quantity than the Tractile roof tile over a square metre roofing application.[20] Therefore, the concrete tile gains an embodied energy value of 39 kg CO_{2eq} from the landfill process and the associated transportation whereas the Tractile roof tile has 3.1 kg CO_{2eq}.

Overall, the total embodied energy results for the life cycle of the concrete tile and the coated steel sheeting are 243 and 3,199 kg CO_{2eq} per square metre respectively for the maintenance scenario. Figure 3.10 (a) shows that the embodied energy for the life cycle of a square metre of a Tractile tile for the maintenance inclusion scenario can be significantly reduced by 90 % and 99.2% when it is fabricated from the Tractile roof tile instead of the concrete tile and the metal and pigment coated steel sheeting. This dramatic reduction occurs at the maintenance stage which requires fuel consumption from the inspection process and is due to the embodied energy being 100% higher for the concrete tile and the coated steel sheeting as Tractile require no maintenance during its warranty of 50 years.

Furthermore, for the exclusion of the maintenance scenario, the embodied energy of the two traditional roofing materials is 74 and 13 kg CO_{2eq} per square metre respectively. The embodied energy of Tractile is 25 kg CO_{2eq} for both scenarios as it requires no maintenance inspection during the usage of 50 years. In this case, Figure 3.9 (b) illustrates that Tractile performs better than the concrete tile by 66% but has a higher embodied energy than the coated steel metal by 48%. This is owing to the fact that Tractile requires less material for a square metre of roofing than the concrete tile whereas for the coated steel sheeting case, Tractile uses higher quantities of the raw materials for the application which requires slightly higher fuel consumption and it cannot be recycled.

Figures 3.11 (a) and (b) present the total environmental impact results which are assessed by the Eco-Indicator 99 H/A 1.03 (EI99 1.03) method as introduced in Section 3.2.2. Figure 3.11 (a) illustrates the total environmental impact results for the inclusion of the maintenance activities which are assumed based on the warranty conditions of the product during 50 years life span.

[20] In this case, concrete roof tile uses 55 kg per square metre whereas Tractile used only 10 kg per square metre.



(a) (b)

Figure 3.11: Comparison of total environmental impact results for a square metre of the three roof sheeting

The results of the maintenance inclusion reveal that the embodied energy of the roof tile at the material and manufacturing process life cycle stage are 3 and 2.1 points per square metre for the concrete tile and the metal and pigment coated steel sheeting respectively. The tractile roof tile has relatively lower embodied energy at 0.6 point per square metre. This difference between the Tractile roof tile and the two traditional roofing materials equate to 80% and 72% respectively. The reason for this, is due to the fact that there is a high human health impact as a result of a relatively high amount of particulate matter of dust which is produced during the production of the silica sand uses 60% for raw materials of concrete tile. Similarly, the high impact of the steel sheeting is due to the limestone which is used for the steel production also generating a relatively large amount of dust which can cause breathing problems to human health. Moreover, as a second set of steel sheets and screws are assumed to be replaced at the 25th year due to its 25 year warranty limitation, the environmental impact is generated even more.

On the other hand, if the maintenance activities are excluded from the life cycle as presented in Figure 3.11 (b), the coated steel sheeting is still higher than Tractile by 50%. This is due to similar reasons as stated above.

For the installation activity, the Tractile roof tile is higher than the two traditional roofing materials due to the higher quantity of steel battens which are used during the installation. Nevertheless, the intrinsic difference is the fuel consumption during the installation, where the Tractile roof tile uses 0.02 point per square metre but the concrete tile consumes 0.08 point per square metre This indicates that the Tractile roof tile reduces the total environmental impact by up to 75% from the fuel consumption used in the installation transportation for the concrete tile.

Another main advantage of the Tractile roof tile is found in the maintenance activities where it consumes zero embodied energy as there is no maintenance required. The coated steel sheeting and the concrete roof tile on the other hand may require intensive transportation from the inspection requirements of the warranty. For the inspection of every 4 months during the 50 year life span, the metal and pigment coated steel sheeting would consumes 149 points from the fuel consumption of the associated transportation. For the inspection requirement of every six years during the 50 year life span of the concrete tile, it would consume 8 points.

However, the end-of-life or the disposal life cycle stage of the metal coated steel sheeting performs better than the Tractile roof tile and concrete tile. This is because an assumption is made that 70% of the steel could be recycled[21], whereas the Tractile roof tile, concrete tile and timber were assumed as 100% landfill[22]. Therefore, the embodied energy of the galvanised steel roof sheet at this stage is -0.27 point for the maintenance inclusion scenarios and -0.13 point for the no maintenance scenarios. The negative values indicate that the total environmental impact is reduced from the recycling process by 0.27 and 0.13 points respectively[23]. Nonetheless, at this stage the Tractile roof tile performs significantly better than the concrete tile as shown in Figure 3.11 (b). It requires higher quantity than the Tractile roof tile for a square metre roofing application.[24] Therefore, the concrete tile gains an embodied energy value of -0.04 point from the landfill and the recycling process of the steel battens and screws as well as the associated transportation whereas the Tractile roof tile has the total environmental impact value of 0.26 point.

Overall, the total environmental impact results for the life cycle of the concrete tile and the coated steel sheeting are 12 and 152 points per square metre respectively for the maintenance scenario. Figure 3.11 (a) shows that the environmental impact for the life cycle of a square metre of the Tractile tile for the maintenance inclusion scenario can be significantly reduced by 89 % and 99.2% when it is fabricated from the Tractile roof tile instead of concrete or metal and pigment coated steel sheeting. This dramatic reduction occurs at the maintenance stage which requires high fuel consumption from the inspection process and is due to the embodied energy being 100% higher for the concrete tile and the coated steel sheeting as Tractile require no maintenance during its warranty of 50 years.

Furthermore, for the exclusion of maintenance scenario, the environmental impact of the two traditional roofing materials is 4.19 and 1.21 points per square metre respectively. The environmental impact of Tractile is 1.27 points for both scenarios as it requires no maintenance inspection during the usage of 50 years. In this case, Figure 3.11 (b) illustrates that Tractile performs better than the concrete tile by 70% but has a slightly higher environmental impact than the coated steel metal by 5%. This is owing to the fact that Tractile requires less material for a square metre of roofing than the concrete tile whereas for

---

[21] The assumptions were made based on the household waste data from Australian data 2007 library of the Life Cycle Assessment software as shown in Appendix C.

[22] The assumptions were made based on the provided input data from B-Pod Pty Ltd.

[23] The maintenance scenario has a higher embodied energy value to the calculation being based on two sets of coated steel sheeting.

[24] In this case, concrete roof tile uses 55 kg per square metre where as Tractile used only 10 kg per square metre.

the coated steel sheeting case, Tractile uses higher quantities of the raw materials for the application which requires slightly higher fuel consumption and it cannot be recycled.

According to Figures 3.9 to 3.11, a square metre of the Tractile roof tile which is manufactured from glass reinforced plastic of B-Pods Pty Ltd has a significantly lower environmental impact than the one that is made from concrete for both inclusive and exclusive maintenance scenarios. Whereas, for the metal and pigment coated steel sheet, Tractile has significantly less environmental impact for the maintenance inclusion scenario and is slightly higher than the metal and pigment coated steel sheet for the other scenario. The gained benefits in making a roof tile out of glass reinforced plastic rather than concrete or metal and pigment coated steel sheeting are described in the following six points.

For the maintenance inclusion scenario:

- In terms of the energy consumption, Tractile roof tile can reduce its energy consumption during its life cycle by up to 92% and 99.5% respectively;
- Tractile roof tile can reduce the amount of greenhouse gases emitted into the atmosphere by 90% and 99.2% respectively during its life cycle;
- Tractile roof tile can reduce the total environmental impacts that can effect human health, the ecosystem quality and resource use by 89% and 99.2% respectively.

For the maintenance inclusion scenario:

- In terms of the energy consumption, Tractile performs better than a concrete tile by 37%;
- A roof tile that is made from Tractile can reduce the amount of greenhouse gases emitted into the atmosphere by 66% when compared to a concrete tile;
- Tractile roof tile can reduce the total environmental impacts that can effect human health, the ecosystem quality and resource use by 70 % when compared to a concrete tile.

On the whole, these benefits are mainly gained during the material and usage stages of the roof tile life cycle. This is because Tractile requires less quantity and is lighter than a concrete tile and also requires no maintenance during the usage stage which saves on fuel from the associated transportation. However, Tractile has a higher embodied energy than the galvanised steel sheeting due to it require larger quantity and has a different disposal options.

3.6 Conclusion

This chapter presented the cradle-to-factory and the cradle-to-grave analyses which assessed the embodied energy for the raw materials of glass reinforced plastics and the roof tile that are made from Tractile roof tile, concrete roof tile and the metal and pigment coated steel sheeting. The methodology overview was presented by defining the scopes and assumptions of the input data which was required for the calculation of the embodied energy analysis. The Life Cycle Assessment method was selected to calculate the embodied energy of the raw materials and the three different roofing materials. This assessment produced two embodied energy results and a full Life Cycle Assessment result. They were the primary energy consumption, the greenhouse gas emissions and the total environmental impacts.

These results were expressed in a unit of MJ_{eq}, kg CO_{2eq} and points respectively. The MJ_{eq} and kg CO_{2eq} results were the generic embodied energy values, however, these two units are only considered the primary energy consumptions and the greenhouse gas emissions. Therefore, the points results were generated from the full Life Cycle Assessment which covers all emission substances that can affect the environment in terms of human health, ecosystem and resource (fossil fuels and mineral) use. Thereafter, the description of the raw materials and the three different roof tile materials were specified. The input data of the cradle-to-factory and the cradle-to-grave analyses was determined on the basis of the scopes, assumptions and descriptions.

The embodied energy results of the cradle-to-factory analysis demonstrated that the raw materials of a kilogram of the Tractile roof tile provided a primary energy source of 11.23 MJ_{eq}, reduced greenhouse gas by 1.11 kg CO_{2eq} and has 0.047 points of the total environmental impact. 80% to 39% of these results are contributed by the raw material extraction and 4.5% to 20% from the transportation of the raw materials. The suggestions for reducing the embodied energy of the glass reinforced plastics were given in two different directions including using low embodied energy raw materials and/or choosing suppliers that use a delivery transportation method that has a low embodied energy.

Subsequently, a hot spots analysis was performed to identify the raw materials or the suppliers that have significantly high embodied energy. Whilst, the embodied energy of the raw materials (M2) and (M4) are significantly higher than other raw materials, the transportation of the raw materials (M4), (M1) and (M2) are also substantially high. Some recommendations were given, such as change to local manufacturers and avoiding as practically as possible the use of road transportation by leaning towards water and rail transportation.

The embodied energy results for the life cycle of a square metre of roof tile were assessed using the cradle-to-grave analysis. The roof tile materials that were examined were the Tractile roof tile, concrete tile and the metal and pigment coated steel sheeting. These results illustrate that the embodied energy of Tractile is considerably lower than the concrete tile for both maintenance scenarios in regards to several factors. The raw material extraction is reduced significantly during the material stage as it uses less quantity than a concrete tile. The fuel consumption decreases dramatically for the transportation involved in the maintenance activities during the usage stage. Low fuel consumption and less energy was required for the end-of-life stage. For the coated steel sheeting, Tractile performs significantly better than the coated steel sheet as it requires no maintenance activities. However, Tractile has higher embodied energy and slightly higher environmental impact than the coated steel sheeting as it uses higher quantities of raw materials which effect the fuel consumption, as well as it cannot be recycled at this present time.

The total embodied energy results of the three roof tile life cycles revealed that:

For the maintenance inclusion scenario:

- A square metre of roofing that is made from Tractile roof tile consumes 92% and 99.5% less energy than a concrete tile and a coated steel sheeting during their life cycle;
- A square metre of roofing that is made from Tractile roof tile emits 90% and 99.2% less greenhouse gases during their life cycles compared to a concrete tile and coated steel sheeting;
- A square metre of roofing that is made from Tractile roof tile has an environmental impact which is 89% and 99.2% than that of a concrete tile and a coated steel sheeting. This equates to a lessening on the effects towards human health, the ecosystem quality and resource use during their life cycle.

For the maintenance inclusion scenario:

- A square metre of roofing that is made from the Tractile roof tile consumes 37% less energy than a concrete tile;
- A square metre of roofing that is made from the Tractile roof tile emits 66% less greenhouse gases during their life cycles compared to a concrete tile;
- A square metre of roofing that is made from the Tractile roof tile has an environmental impact which is 70% lower than that of a concrete tile.

CHAPTER 4

AMPELITE FIBREGLASS PTY LTD -EMBODIED ENERGY OF ROOF SHEETING

4.1 Introduction

Ampelite Fibreglass Pty Ltd[25] manufactures Wonderglas GC and Webglas GC sheeting which are made of a fibreglass reinforced polyester. Wonderglas GC is a transparent roof sheeting which is made from gel coated polyester with a UV resistant gel coating of 100 microns in thickness. This gel coat helps to reduce surface erosion and loss of light transmission. As Wonderglas GC has a very high resistance to a range of common chemicals, it comes with a 25 year warranty.

Webglas GC is suitable for a high corrosion environment as it has high corrosive resistance. Therefore, it can be used where metal and other roofing deteriorate or corrode at an unacceptable rate. The weight of Webglas is 3600 grams per square metre which is considerably lighter than conventional sheeting that are made from sheet metal. This sheeting is reinforced with a heavy gauge woven glass mat which provides continuous reinforcement in every direction. Webglas provides a 20 years warranty for surface erosion.

Both Wonderglas GC and Webglas GC sheeting are fabricated by using the pultrusion process which comprises of four main steps, namely reinforcement, pultrusion die, pulling unit and sawing unit [2]. Generally, the material selection for roof sheeting depends on the structural integrity, the capital investment and environmental requirement of the application. The fibreglass reinforced polyester sheeting does have some physical and economical advantages over traditional materials.

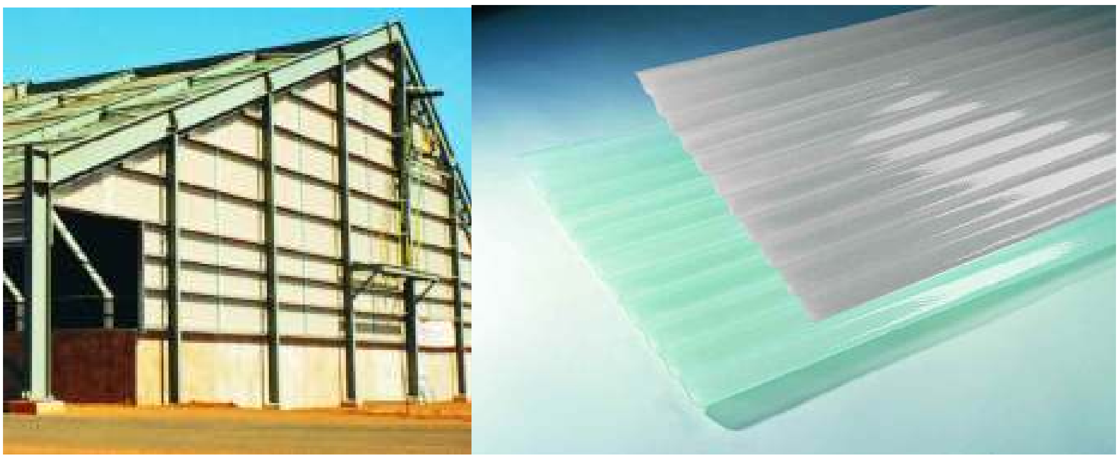


Figure 4.1: Composite roof sheet.

---

[25] http://www.ampelite.com.au/fibreglass.htm

However, in terms of their environmental performance, it is not so clear and therefore this project was aimed to quantify the embodied energy of the Wonderglas GC and Webglas GC. Therefore, this chapter aims to assess the embodied energy of raw materials that are used to make a kilogram of Wonderglas GC sheeting. Moreover, the embodied energy analysis is used to compare a square metre of roof sheeting made of Wonderglas GC, Webglas GC and galvanised steel sheeting. Life Cycle Assessment is used as a tool to calculate the embodied energy of a kilogram of Wonderglas GC and the three different roof sheeting.

Cradle-to-factory analysis[26] is used in this chapter to determine the embodied energy of the raw materials required to make a kilogram of Wonderglas GC sheeting which is manufactured by Ampelite Fibreglass Pty Ltd to produce a gel coated polyester sheeting. In addition, cradle-to-grave analysis is employed to compare the embodied energy of the life cycle for a square metre of roof sheeting made of the Wonderglas GC, Webglas GC and galvanised steel sheeting. Theoretically, cradle-to-grave analysis is an assessment of a product life cycle including raw material extraction, manufacturing process, usage, transportation and end-of-life stages.

The outline of this chapter is as follows:

- Methodology overview of the cradle-to-factory and the cradle-to-grave analyses
- General scopes and assumptions of the analyses
- Description of a kilogram of Wonderglas GC
- Description of 1 square metre of roof sheeting that is made from Wonderglas GC, Webglas GC and galvanised steel sheeting.
- Input data for the cradle-to-factory and the cradle-to-grave analyses
- Cradle-to-factory results and discussion: the embodied energy of the raw materials required to make a kilogram of Wonderglas GC.
- Cradle-to-grave results and discussion: the comparison between 1 square metre of Wonderglas GC, Webglas GC and galvanised steel sheeting.

---

[26] Technically, the cradle-to-factory (gate) analysis is commonly defined as “an assessment of a partial product life cycle from manufacture ('cradle') to the factory gate before it is transported to the consumer” (Reference: Moreno, A., 2008, The DEPUIS HANDBOOK Chapter 4: Methodology of Life Cycle Assessment, Accessed: October 2009, http://www.depuis.enea.it/dvd/website.html). However, cradle-to-factory analysis in this project is specified as the embodied energy incurred during the raw material extraction and the transportation from suppliers to manufacturers.

- Conclusion is drawn in the last section of the chapter

4.2 Methodology Overview

4.2.1 Embodied energy analysis

In this study, the embodied energy analysis of roof sheeting comprises of the cradle-to-factory and the cradle-to-grave analyses as illustrated in Figure 4.2. These analyses employ the Life Cycle Assessment method to assess the environmental impacts of all life cycle stages as shown in Figure 4.2. The methodology of these two analyses is described briefly as follows.

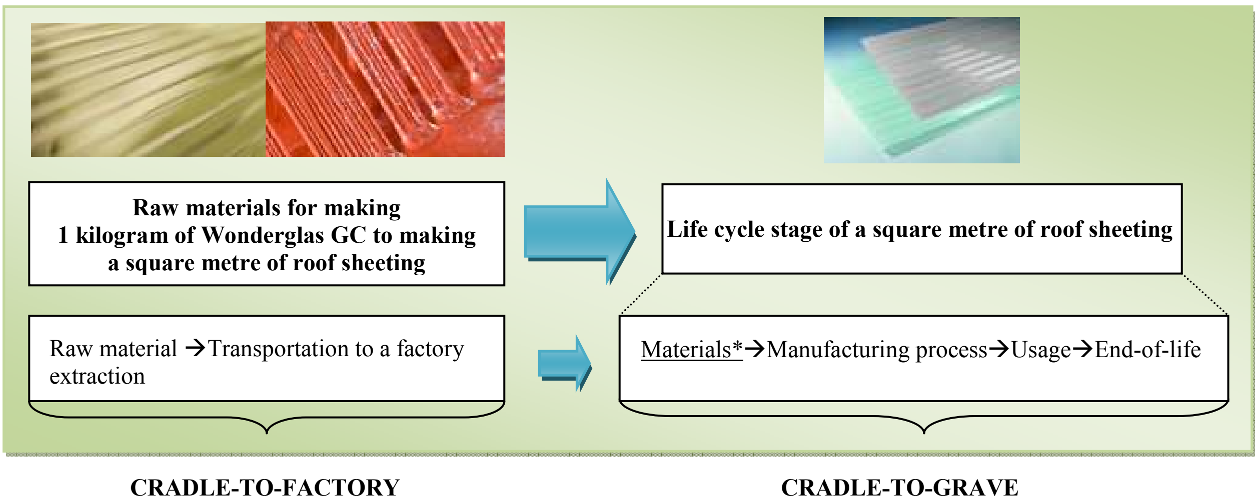


Figure 4.2: The scopes of the cradle-to-factory and the cradle-to-grave analyses.[27]

The methodology of these two analyses is described briefly as follows. Firstly, the cradle-to-factory analysis assesses the embodied energy in making a kilogram of Wonderglas GC as presented in the left portion of Figure 4.2. This analysis focuses on two main embodied energy sources. They are the raw material extraction and the transportation of raw materials from the supplier to a factory, i.e. Ampelite Fibreglass Pty Ltd. The asterisk sign next to the word 'Materials' in Figure 4.2 indicates that the embodied energy result from this analysis will be used as the input data for the materials stage in the cradle-to-grave analysis.

Secondly, the cradle-to-grave analysis as shown in Figure 4.2 calculates the life cycle of a square metre of Wonderglass GC sheeting. For comparison purposes, this analysis technique is also performed on

[27] The photographs were taken from www.exelcomposites.com and www.ampelite.com.au.

a square metre of Webglas GC and galvanised steel sheeting. The life cycle stages of these products are presented on the right hand side of Figure 4.2 where:

- The materials stage is the total raw materials that are used in making the three roof sheeting;
- The manufacturing process stage comprises the processes involved in making the roof sheeting;
- The usage stage consists of the activities that occur after the roof sheeting is manufactured i.e. the installation process until the product is disposed of. In this case, the usage period is assumed as 25 years;
- The end-of-life stage is the disposal scenario which includes the transportation of the roof sheeting to the disposal site and the disposal process.

Finally, the embodied energy and the environmental impacts results from the cradle-to-factory analysis are discussed and the hot spots identified. For this project a hot spot is defined as the raw materials and/or suppliers which have a high contribution to the embodied energy results. The hot spots analysis was conducted in order to make further suggestions in order to minimise or eliminate the identified raw materials and/or suppliers. Subsequently, the embodied energy results from the cradle-to-grave analysis of a square metre of Wonderglas GC sheeting are analysed and compared with the life cycle of a square metre of Webglas GC and galvanised steel sheeting.

4.2.2 Scopes and assumptions of the embodied energy analysis

This section presents Tables 4.1 and 4.2 to clarify the scopes and assumptions that were made for the cradle-to factory and the cradle-to-grave analyses. Table 4.1 provides the main scope of the cradle-to-factory analysis which focuses on quantifying the embodied energy of raw materials used in making a kilogram of Wonderglas GC. Subsequently, the scopes of the input data that are associated with the raw material extraction and their transportation are given in Table 4.1. Furthermore, Table 4.1 shows the data sources that are used to make the assumptions for the input data of the cradle-to-factory analysis. Overall, the input data in terms of the quantities and the types of materials and transportation were provided by Ampelite Fibreglass Pty Ltd.

The rest of the data was obtained by using further literature reviews and the libraries from the database of the LCA software, SimaPro 7.1.8. For instance, the input data for the amount of raw material was based on the information from the Material Safety Datasheets (MSDs) which were provided by Ampelite Fibreglass Pty Ltd. The material types were assumed using the Australian Data 2007 (AU) library and the distance of the transportation of raw materials was found using the online maps provided by Google.

CRADLE-TO-FACTORY							
Scope: To quantify the embodied energy of the raw materials in making 1 kilogram of Wonderglas GC.							
Input data	Amount of the raw materials used in making 1 kilogram of Wonderglas GC.						
Material life cycle stage	**Scopes and assumptions**	**Data sources**					
		AM	LR	AU	ET	ID	IN
Raw material extraction	Amount of raw materials (kg)	✓					
	Material types	✓(MSDs)	✓	✓	✓	✓	✓
Transportation of raw materials: *From:* Suppliers *To:* Ampelite Fibreglass Pty Ltd (Victoria)	The locations of suppliers	✓					
	Distance (km): Measure by using the online maps	✓					
	Transportation types	✓		✓			

Note:Ampelite Fibreglass Pty Ltd (AM), Literature review (LR),the 'Australia Data 2007'(AU), the 'ETH-ESU 96' (ET), the 'IDEMAT2001'(ID) and the 'Industry Data 2.0' (IN) libraries are the databases from the SimaPro 7.1.8 software.

Table 4.1: Scopes and assumptions of the cradle-to-factory analysis for Wonderglas GC.

Similarly, Table 4.2 presents the scopes of the cradle-to-grave analysis for the life cycle of the three roof sheets. The life cycle input data in terms of the quantities and types are assumed based on the data sources as shown in the table.

It is worth highlighting the assumption for the material stage of Wonderglas GC in Table 4.2. The material stage has two embodied energy sources. They are the raw material extraction and the transportation of those materials. In this stage, the embodied energy of the roof sheeting is assumed to be calculated directly from the embodied energy results of the cradle-to-factory analysis. The calculation is carried out by multiplying the embodied energy results from the cradle-to-factory analysis with 2.4 kg per square metre. For instance, the embodied energy result of Wonderglas GC from the cradle-to-factory analysis is 12 MJ_{eq} per kg and the weight of Wonderglas GC sheeting is 2.4 kg per square metre. Therefore, the embodied energy result for the material stage of Wonderglas GC in this cradle-to-grave analysis is:

$$12\ MJ_{eq} \text{ per kg} \times 2.4 \text{ kg per square metr} = 28.8\ MJ_{eq} \text{ per square metre}$$

In addition, further assumptions were made to perform the cradle-to-grave analysis for the life cycle of the three roof sheets. The manufacturing processes input data was specified by another participant company and Ampelite Fibreglass Pty Ltd. The other participant company specified the power consumption as 1.2 kilowatt and 0.35 kilowatt for the cutting as well as the drilling and screwing processes whereas, Ampelite Fibreglass Pty Ltd specified a cutting time of 1 minute.

CRADLE-TO-GRAVE						
Scope: To analyse the embodied energy of the life cycle for 1 square metre of roof sheeting that is made from Wonderglas GC, Webglas GC and galvanised steel sheeting.						
Life cycle stages of the roof sheeting	**Scopes and assumptions**	**Data sources**				
		AU	DA	ET	ID	IN
Material stage: *Input data* *Amount of the raw materials per a square metre of roof tile.* Raw material extraction And Transportation of raw materials *From:* A Supplier *To:* Manufacturers	***Wonderglas GC sheeting:*** - *Wonderglas GC:* 2.4 kg per square metre [a] Multiply the embodied energy results from the cradle-to-factory analysis in the unit of per kg with 2.4 kg per square metre . ***Webglas GC sheeting:*** - *Webglas GC:* 3.66 kg per square metre [a] Multiply the embodied energy results from the cradle-to-factory analysis in the unit of per kg with 3.66 kg per square metre . ***Galvanised steel sheeting:*** - *material used for steel sheet 0.42mm BMT:*4.35 kg per square metre[b] Assumed to have raw materials available local in Australia, no transportation is included.	✓ ✓ ✓		✓ ✓	✓ ✓	✓ ✓
Manufacturing process: *Input data*	***Wonderglas GC sheeting:*** **Process type:** - *Fibre composite (Electricity):* 0.815 kWh per square metre [a] ***Webglas GC sheeting:*** **Process type:** - *Fibre composite (Electricity):* 1.2438 kWh per square metre [a] ***Galvanised steel sheeting:*** **Process type:** - *Steel sheet* [c]*:* - *Energy and electricity for steelsheet* - *Zinc coating, at 65 um double sided:* 1 square metre[c]	✓ ✓ ✓ ✓		✓ ✓		
Usage: *Input data* *From:* Manufacturers *To:* A customer	***All sheeting:*** **Installation process type:** *Materials and processes for roofing are:* *A linear metre of rolled steel battens 0.55mm BMT:* - *Rolled steel battens:* 0.71 kg per square metre [b] *Zinc coating, at 65 um double sided:* 0.159 square metre[c] *6 steel Screws* 0.39 kg per square metre [b] *Electricity for* Cutting roof sheets *Electricity for cutting* steel battens *Electricity for* drilling and screwing [a,b] **Transportation for installation** [b]**:** *Distance* [b]*:* 200 kilometres *By* [b]*:* Articulated truck for freight **Maintenance process type:** No processes are included. [a,b]	✓ ✓ ✓		✓		
End-of-life: *Input data*	***All sheeting:*** **Disposal transportation:** *Distance* [b] *(From a customer to a disposal site):* 200 kilometres *By* [b]*:* Articulated truck for freight	✓				
End-of-life: *Input data* Disposal scenarios	***All sheeting:*** **Disposal process type** *(Household waste scenario)*: 100% landfill for the fibre composites 70% recycling for steel	✓ ✓				

Note: [a] *The data was provided by Ampelite Fibreglass Pty Ltd,* [b] *The data was provided by another participant company.* [c] *Literature review 'Australia data 2007'(AU), the 'Data Archive' (DA), the 'ETH-ESU 96' (ET), the 'IDEMAT2001'(ID) and 'Industry Data' (IN)' libraries which are the databases from the Life Cycle Assessment, SimaPro 7.1.8 software.*

Table 4.2: Scopes and assumptions for the cradle-to-grave analysis of roof sheeting.

The zinc coating process with a thickness of 65 micrometres (µm) double sided was assumed to represent the hot dip galvanised steel process for the steel sheeting and steel battens. This process was based on the ETH-ESU 96 database of the LCA software which is based on the coating process of 920g/m^2 with the thickness of 65µm double sided and 130µm single sided.

Therefore, the coating area of the steel sheet is equal to 1 metre as it represents the coating thickness of 65µm double sided. Whereby, the coating area of the steel batten was estimated as 0.159m^2 which was based on the dimensions of the total top surface area of the roof batten profile 0.55mm BTM[28]. Thus, the coating area is estimated as:

$$(0.015m^2+0.0445m^2+0.04m^2+0.0445m^2+0.015m^2) = 0.159\ m^2$$

The transportation involved during the installation and the disposal of the products was specified by another company. In this instance, to install a roof sheet, the transportation distance from Ampelite Fibreglass Pty Ltd to a customer during the usage stage was assumed to be 200 kilometres. The articulated truck was also assumed as the transportation used in disposing of the roof sheeting at its end-of-life stage.

Table 4.3 is given to clarify the scopes and the assumptions of the embodied energy calculation tool which was selected for the cradle-to-factory and the cradle-to-grave analyses. As a result, three Life Cycle Impact Assessment methods from the SimaPro 7.1.8 software were selected as summarised in Table 4.3. The methods are the Cumulative Energy Demand version 1.04, the IPCC GWP 100a version 1.00 and the Eco-Indicator 99 H/A version 2.03 methods.

Furthermore, Table 4.3 also summarises the calculation approach and the results of the three methods for the cradle-to-factory and the cradle-to-grave analyses. These methods generated the embodied energy results for these analyses in the units of MJ_{eq}, kg CO_{2eq} and points per kg as well as in units of MJ_{eq}, kg CO_{2eq} and points per square metre. Therefore, Figure 4.3 is given to provide additional information to aid in how to interpret these results. Additionally, the amount of six conventional air pollutants as listed in Table 4.3 are given as the total airbourne substances that are emitted during the cradle-to-factory and the cradle-to-grave analyses. The next section presents the material and product description for the cradle-to-factory and the cradle-to-grave analyses.

[28] http://www.stratco.com.au/Products/Steel_Framing/Types/Roof_Ceiling_Battens/roof_ceiling_battens.asp

EMBODIED ENERGY CALCULATION TOOL	
Embodied Energy Analysis	**Scopes and Assumptions**
Embodied energy assessment tool	The Life Cycle Impact Assessment methods from the LCA software, SimaPro 7.1.8 software.
Selection of the Life Cycle Impact Assessment methods	The selection of these methods was based on the generic embodied energy analysis which is often based on the input-output model that is used to quantify the primary energy sources and often expressed in MJ and in kg of CO_2 units. In addition, as the two values from the Cumulative energy demand version 1.04 and the IPCC GWP 100a version 1.00 methods only represent the embodied energy in terms of the primary energy consumption and the impacts from the climate change respectively. Therefore, the points value is also given. This value is calculated from Life Cycle Assessment which considers the impacts on human health, the ecosystem quality and resource use. The points value is calculated from the Eco-Indicator 99 H/A version 2.03 method.

<table>
<tr><th colspan="5">LIFE CYCLE IMPACT ASSESSMENT METHODS</th></tr>
<tr><th rowspan="2">Method</th><th rowspan="2">Calculation Approach and unit</th><th colspan="3">Embodied Energy Results</th></tr>
<tr><th>Cradle-to-factory</th><th>Cradle-to-grave</th><th>Amount of conventional air pollutions</th></tr>
<tr><td>Cumulative energy demand version 1.04</td><td>Calculation: Calculates the embodied energy in terms of the consumption of the primary energy sources such as fossil fuels, minerals, renewable energy.
Unit: MJ_{eq}</td><td>MJ_{eq} per kg</td><td>MJ_{eq} per square metre</td><td rowspan="3">Carbon monoxide (CO)
Carbon dioxide (CO_2)
Nitrogen dioxide (NO_2)
Sulphur dioxide (SO_2)
Unspecified particulate
Volatile organic compounds (VOC)</td></tr>
<tr><td>IPCC GWP 100a version 1.00</td><td>Calculation: Calculates the greenhouse gas emissions which impact the global warming.
Unit: kg CO_{2eq}</td><td>kg CO_{2eq} per kg</td><td>kg CO_{2eq} per square metre</td></tr>
<tr><td>Eco-Indicator 99 H/A version 2.0</td><td>Calculation: calculates as the environmental performance indicator as a single score. This is a comprehensive Life Cycle Assessment analysis which considers human health, the ecosystem quality and resource use impacts.
Unit: points of a single score</td><td>points per kg</td><td>points per square metre</td></tr>
</table>

Table 4.3: Scopes and assumptions for the embodied energy calculation tools and results.

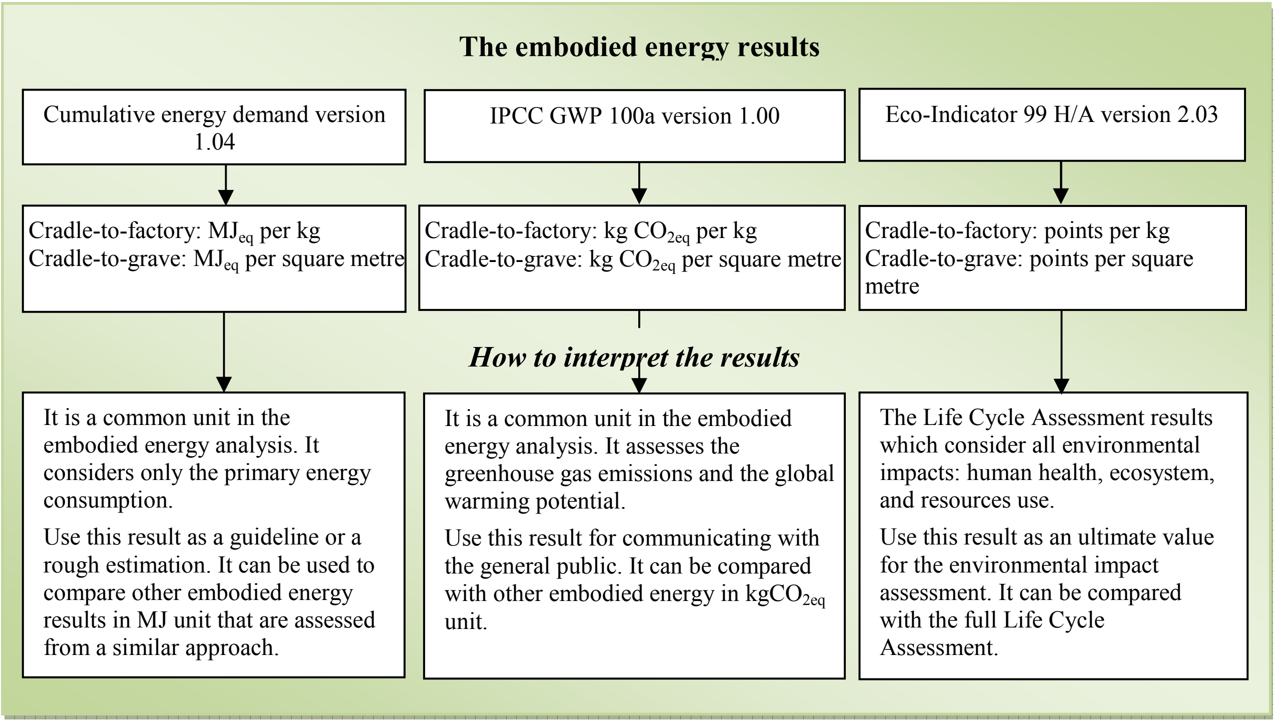


Figure 4.3: How to interpret the embodied energy results.

4.3 Material and Product description

4.3.1 Fibre composite description

The description of the raw materials used in manufacturing of the fibre composite is summarised in Table 4.4. Various raw materials constitute the composite material such as fibreglass, plastic resins and ‘others’ which include pigment, catalysts and additives. These raw materials are supplied by eight suppliers from Australia, Asia and US regions. The transportation of the raw materials from suppliers to Ampelite Fibreglass Pty Ltd located in Victoria involves road and water transportation. The transportation of the raw materials is presented in the last column of Table 4.4.

Additionally, Table 4.4 presents the abbreviations of the raw material type ‘M’ and its transportation ‘M_T’ which are provided for later discussion in this chapter. As there are eight suppliers involved in this analysis, M1 to M8 and also M1_T1 to M8_T3 are presented in Table 4.4.

Raw material type	List of raw material	Region of supplier	Road and water transportation of raw material: from a supplier to the factory, Ampelite Fibreglass Pty Ltd (Ampe.)
Fibre glass	M5 (with 3 options of the MSDs)	Asia	Supplier *(M5) → (M5_T1) → (M5_T2) → Factory, (Ampe.) or Supplier *(M5) → (M5_T1) → (M5 _T2) → (M5_T3) → Factory (Ampe.)
Resin	M1, M6, M8	Asia and US	Supplier *(M1) → (M1_T1) → Factory, (Ampe.) Supplier *(M6) → (M6_T1) → (M6_T2) → Factory, (Ampe.) Supplier *(M8) → (M8_T1) → (M8 _T2) → (M8_T3) → Factory (Ampe.)
Others: such as pigment, catalysts, and additives	M2 to M4 and M7	Asia and Australia	Supplier *(M2, M3 and M4) → (M_T1) → Factory, (Ampe.) Supplier *(M7) → (M7_T1) → (M7 _T2) → (M7_T3) → Factory (Ampe)

Note: The abbreviations of 'M' and "M_T" are provided for the discussion of Figure 4.5. Raw material types (M), First transportation of the raw material (M_T1), Second transportation of the raw material (M_T2) and Third transportation of the raw material (M_T3)

(Road transportation such as a truck) and (Water transportation such as an Australian international shipping)

Table 4.4: The raw materials and the transportation of raw materials in making a kilogram of the fibre composite.

4.3.2 A square metre roof sheeting description

The cradle-to-grave analysis focuses on assessing the embodied energy of a square metre of roof sheeting which are made from three materials.

The three roof sheeting comparisons are:

- 1 square metre of Wonderglas GC sheeting, galvanised steel battens and steel screws
- 1 square metre of Webglas GC sheeting, galvanised steel battens and steel screws
- 1 square metre of galvanised steel sheeting, galvanised steel battens and steel screws.

The quantities of the galvanised steel sheeting, the galvanised steel battens and steel screws are based on the assumptions from another participant company. The thickness of the galvanised steel is obtained based on the literature review. The coating thickness of 65 micrometres using the zinc coating was manufactured by using a hot dip process from the ETH-ESU 96 database of the LCA software.

A general description for the roof sheeting life cycle is defied as follows.

7. The functional unit of the case study is based on the life span of 30 years.
8. The cradle-to-grave analysis for a square metre of Wonderglas GC and Webglas GC roof sheeting are made using the provided input data from Ampelite Fibreglass Pty Ltd including the quantities of the materials and electricity consumption for the pultrusion process.
9. The materials which are included as additional components in the cradle-to-grave analysis for a square metre of roof sheeting are the galvanised steel battens and the steel screws. This means that the other common components for a roofing system such as the trusses, the reflective foil sarking and thermal insulation materials are excluded due to lack of information from the manufacturer.
10. The usage stage involved the installation process involves the installation transportation, the electricity required in cutting the roof sheeting, the steel battens, also the drilling and screwing processes for the fasteners.
11. The maintenance activities of these products are excluded as they are assumed to be the same in all materials.
12. The End-of-Life (EOL) stage involves the transportation for disposing the product. Also, the disposal process is assumed based on the Australian data 2007.

4.4 Input Data

The input data of the cradle-to-grave analysis for the three roof sheets namely Wonderglas GC, Webglas GC and the galvanised steel sheeting are presented in Tables 4.5 and 4.6 respectively. This input data was derived from the scopes and the assumptions in Section 4.2.2. Therefore, the input data of all life cycle stages are presented in terms of a unit, the amount and the 'material/process description' which represents the material and the manufacturing process types[29].

[29] In relation to this, the data sources for the input data of 'Material/process description' and 'Amount' are also given in the last column of Tables 4.5 and 4.6 for the reference of the database background.

Life cycle stage	Materials/Processes description	Unit	Amount	Database
Material	Wonderglas GC	kg	2.4	Multiply 1kg results from the cradle-to-factory analysis by 2.4
Process	Total electricity consumption for pultrusion process	kWh	0.815	Australian data 2007
Usage: Installation transportation	Rolled steel battens	kg	0.71	Australian data 2007
	Zinc coating for steel battens	m^2	0.159	ETH-ESU 96 and Australian data 2007
	Steel screws production	kg	0.39	Data archive
	Cutting sheeting (1/60hour×1.2kw)	kWh	0.02	Australian data 2007
	Cutting steel battens (1/60hour×1.2kw)	kWh	0.02	Australian data 2007
	Drilling & screwing; Cordless drill (1/60hour×0.35kw)	kWh	0.0058	Australian data 2007
	Articulated truck freight, customisable/AU U: (2.4+0.71+0.39kg*200km/1000)	tkm	0.7	Australian data 2007
End-of-life: Disposal transportation	Articulated truck freight, customisable/AU U: (3.5kg*200km/1000)	tkm	0.7	Australian data 2007
End-of-life: Household waste	Australian household waste: 100% landfill for the fibre composite and 70% for steel recycling	%	100	Australian data 2007

Table 4.5: Input data for a square metre of Wonderglas GC roof sheeting.

Life cycle stage	Materials/Processes description	Unit	Amount	Database
Material	Webglas GC	kg	3.66	Multiply 1kg results from the cradle-to-factory analysis by 3.66
Process	Total electricity consumption for pultrusion process	kWh	1.244	Australian data 2007
Usage: Installation transportation	Rolled steel battens	kg	0.71	Australian data 2007
	Zinc coating for steel battens	m^2	0.159	ETH-ESU 96 and Australian data 2007
	Steel screws production	kg	0.39	Data archive
	Cutting sheeting (1/60hour×1.2kw)	kWh	0.02	Australian data 2007
	Cutting steel battens (1/60hour×1.2kw)	kWh	0.02	Australian data 2007
	Drilling & screwing; Cordless drill (1/60hour×0.35kw)	kWh	0.0058	Australian data 2007
	Articulated truck freight, customisable/AU U: (2.4+0.71+0.39kg*200km/1000)	tkm	0.952	Australian data 2007
End-of-life: Disposal transportation	Articulated truck freight, customisable/AU U: (3.5kg*200km/1000)	tkm	0.952	Australian data 2007
End-of-life: Household waste	Australian household waste: 100% landfill for the fibre composite and 70% for steel recycling	%	100	Australian data 2007

Table 4.6: Input data for a square metre of Webglas GC roof sheeting.

Life cycle stage	Materials/Processes description	Unit	Amount	Database
Material: Steel sheet	Material for making Steel sheet, 5% recycled/AU U	kg	4.35	Australian data 2007
Process	Energy and electricity for making Steel sheet, 5% recycled/AU U	kg	4.35	Australian data 2007
	Hot-dip galvanisation process: Zinc coating steel sheet	m^2	1	ETH-ESU 96 and Australian data 2007
Usage: Installation transportation	Rolled steel battens	kg	0.71	Australian data 2007
	Zinc coating Steel battens	m^2	0.159	ETH-ESU 96 and Australian data 2007
	Steel screws production	kg	0.39	Data archive
	Cutting sheeting (1/60hour×1.2kw)	kWh	0.10	Australian data 2007
	Cutting steel battens (1/60hour×1.2kw)	kWh	0.02	Australian data 2007
	Drilling & screwing; Cordless drill (1/60hour×0.35kw)	kWh	0.0058	Australian data 2007
	Articulated truck freight, customisable/AU U: (4.35+0.71+0.39kg*200km/1000)	tkm	1.09	Australian data 2007
End-of-life: Disposal transportation	Articulated truck freight, customisable/AU U: (5.45kg*200km/1000)	tkm	1.09	Australian data 2007
End-of-life: Household waste	Australian household waste: 100% landfill for Fibre composite and 70% for steel recycling	%	100	Australian data 2007

Table 4.7: Input data for a square metre of galvanised steel sheeting.

4.5 Embodied Energy Results

4.5.1 Cradle-to-factory results and discussion

The cradle-to-factory analysis was carried out by using the Life Cycle Assessment method to assess the embodied energy of the raw materials that are comprised in a kilogram of Wonderglas GC as shown in Figure 4.4.

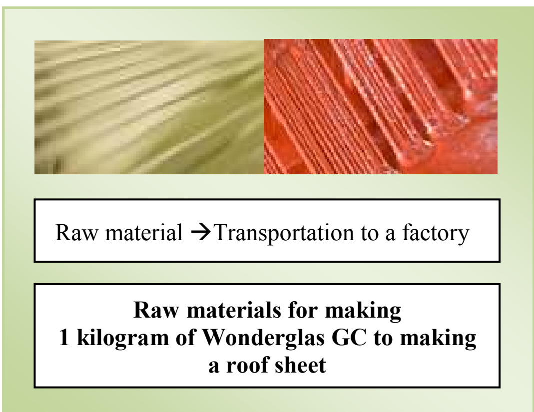


Figure 4.4: Two main embodied energy sources of the cradle-to-factory analysis.

This assessment produced the embodied energy results in three different environmental aspects. They are the primary energy consumption, the greenhouse gas emissions and the total environmental impacts or a single score. These results are expressed in a unit of MJ_{eq} per kg, kg CO_{2eq} per kg and points per kg respectively. These charts display the results in terms of the raw material extraction and the transportation of the raw materials from suppliers to Ampelite Fibreglass Pty Ltd. The last bar of the charts gives the total results of the two main embodied energy sources which are the sum of the raw material extraction and the transportation of the raw materials.

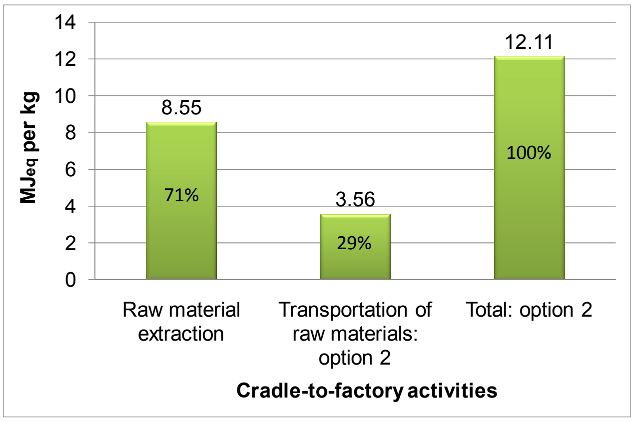
The total results of these two embodied energy sources are also provided in the last bar of Figures 4.5 (a) to (c). On the whole, the raw materials for a kilogram of fibre composite gives a total embodied energy result of 12 MJ_{eq}, 0.6 kg CO_{2eq} and 0.05 points. These total embodied energy results are contributed by 62% to 71% from the raw material extraction and 29% to 38% from the transportation of the raw materials as labelled in Figure 4.5.

The distinct contributions of the two embodied energy sources are clearly revealed. The finding suggests that the embodied energy of the fibre composite can be reduced in two different directions.
The first direction is to reduce the high embodied energy of the raw material extraction by using alternative raw materials with low embodied energy. The second direction is to be selective in choosing the suppliers in order to ensure low embodied energy in their delivery transportation.

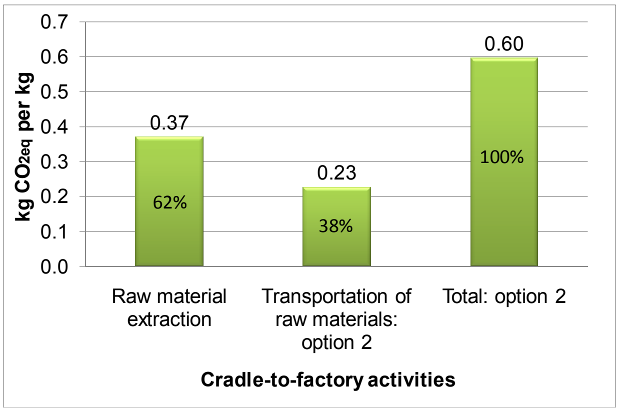
Ideally, the first direction would be the best option as it can reduce the embodied energy dramatically by changing some of the raw materials, as the raw material extraction actually contributes a large portion in the total embodied energy result. However, it requires further research and development in finding an alternative or a new raw material which requires further investment of the supporting systems.

Therefore, this direction can only be targeted as a long term product development plan. In practice, the second direction would be more attractive as it is a fast and a simple approach which requires only a careful consideration in selecting the suppliers. For instance, the selected suppliers should supply the raw materials that are manufactured locally or require less energy-intensive transportation systems for transporting the raw materials.

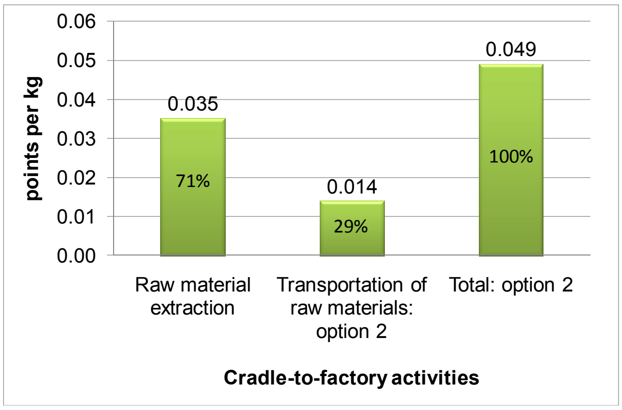
To enhance the implementation of these suggestions, Figure 4.6 explicitly presents the embodied energy for each raw material and its corresponding transportation method. These results are produced from the detailed input data such as the MSDs and the actual location of the suppliers for all raw materials provided by Ampelite Fibreglass Pty Ltd.



(a) Primary energy consumption results

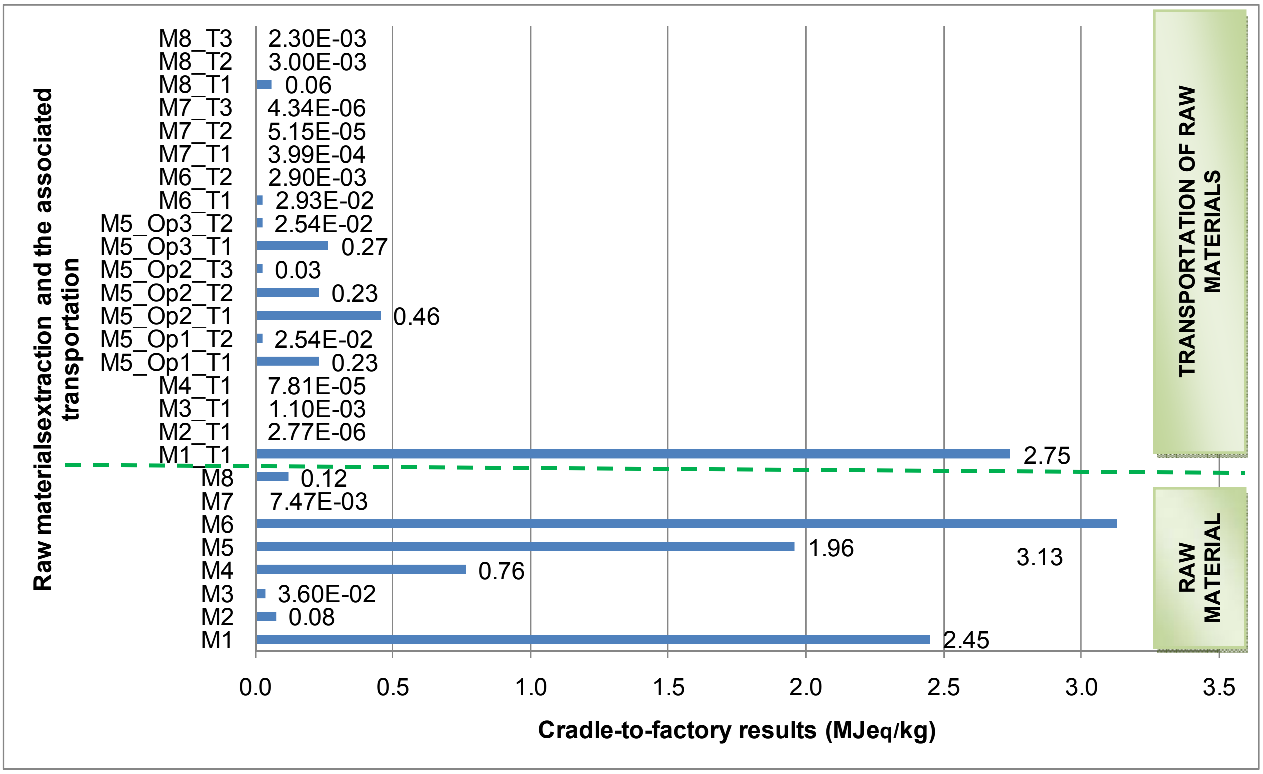


(b) Greenhouse gas emissions results



(c) Total environmental impacts results

Figure 4.5: Embodied energy results of cradle-to-factory analysis for the Wonderglas GC of Ampelite Fibreglass Pty Ltd.



Note:Raw material types (M), First transportation of the raw material (M_T1), Second transportation of the raw material (M_T2), Third transportation of the raw material (M_T3), Fourth transportation of the raw material (M_T4),

Figure 4.6: Detailed embodied energy results (MJ_{eq}/kg) of Wonderglas GC for all raw materials and transportation of raw materials involved.

Figure 4.6 reveals that the embodied energy of Wonderglas GC from Ampelite Fibreglass Pty Ltd was dominated by the combination of several raw materials which originated from overseas suppliers. As a result, a number of hot spots related to the raw materials or the suppliers that have significantly high values are revealed in Figure 4.6.

On this occasion, the raw material (M6) contributes the most followed by the raw material (M1), (M5) and (M4). The clear hot spots for the supplier's transportation are the transportation of the raw materials (M1), (M5) and (M8). Similarly, these higher contributions of the embodied energy for the transportation methods were observed with notable reasons. Since these raw materials were required in high quantities, they needed to be imported from overseas. Therefore a combination of transportation types was utilised. At the same time, some of the locally-supplied raw materials also needed to be transported on road over a significantly long distance i.e. the transportation of raw material (M1) from Queensland to Victoria.

Consequently, these hot spots can be minimised and eliminated by approaching the following recommendations.

- Change the raw material (M6), (M1), (M5) and (M4) to alternative materials which have lower embodied energy in their raw material extraction;

- Change the raw material (M6), (M1), (M5) and (M4) to alternative materials which have lower embodied energy in their raw material extraction;
- Change the suppliers of the raw material (M5) and (M8) to local manufacturers. This applies particularly to the raw material (M8) which came from the US region and also required long distance travel by road transportation;
- Improve the transportation system by avoiding the use of road transportation over a long distance;
- Change the transportation types by leaning more towards water and rail transportation.

4.5.2 cradle-to-grave results and discussion

As in the CTG analysis, the Life Cycle Assessment method was used to assess the embodied energy of the whole life cycle of a square metre of Wonderglas GC, Webglas GC and galvanised steel sheeting as shown in Figure 4.7. This assessment produced the embodied energy results of the primary energy consumption, the greenhouse gas emissions and the full Life Cycle Assessment for the total environmental impacts. These results are expressed in a unit of MJeq per square metre, kg CO_{2eq} per square metre and points per square metre respectively.

As in the cradle-to-grave analysis, the Life Cycle Assessment method was used to assess the embodied energy of the whole life cycle of a square metre of Wondergla GC, Webglas GC and galvanised steel sheeting as shown in Figure 4.7. This assessment calculated the embodied energy results of the primary energy consumption and the greenhouse gas emissions and also the total environmental impacts from a detail Life Cycle Assessment. These results are expressed in a unit of MJ_{eq} per square metre, kg CO_{2eq} per square metre and points per square metre respectively.

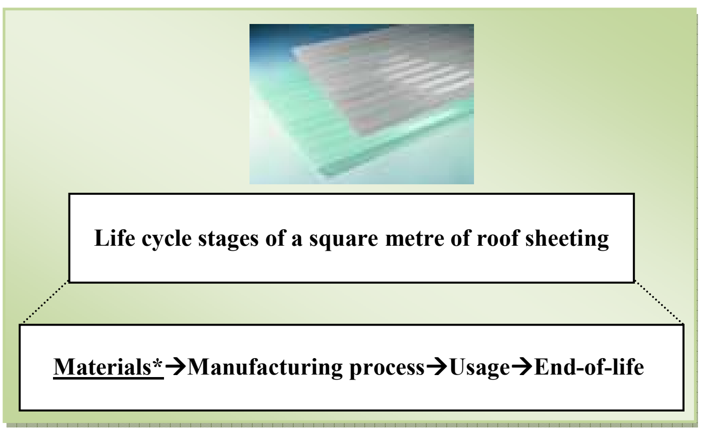


Figure 4.7: Life cycle stages of a square metre roof sheet.

In this section, the three results of all roof sheeting are presented in Figures 4.8 to 4.10. These charts display the results in terms of the life cycle stages which are the materials, manufacturing process, usage and end-of-life stages as illustrated in Figure 4.7. The last bar of the charts gives the total result of the two roof sheets which are the sum of the four life cycle stages. The blue bar represents the galvanised steel sheeting, the green bar shows Wonderglas GC roof sheeting and the red bar illustrates Webglas GC roof sheeting.

Figure 4.8 presents the embodied energy results of the primary energy consumption which was assessed by the Cumulative Energy Demand version 1.04 (CED1.04) method as introduced in Section 4.2.2. The embodied energy of the roof sheeting at the material life cycle stage are 101 MJ_{eq} per square metre for the galvanised steel sheeting and 29 and 45 MJ_{eq} per square metre for Wonderglas GC and Webglas GC sheeting respectively. This difference between the fibreglass reinforced polyester sheeting and the galvanised steel sheeting equate to 71% and 55% respectively. The reason for this is due to the fact that a relatively high amount of energy is required during the steel extraction process.

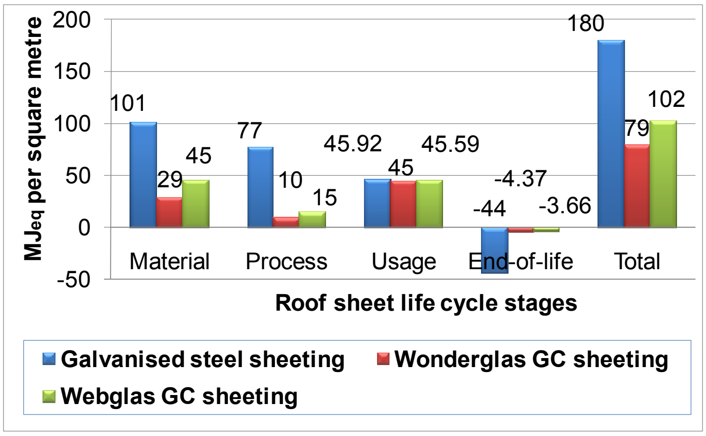


Figure 4.8: Comparison of primary energy consumption results for a square metre of the three roof sheeting.

Another advantage of Wonderglas GC and Webglas GC roof sheeting are found at the manufacturing process where its embodied energy is significantly lower than the galvanised steel sheeting by 87% and 81% respectively. This is owing to the galvanised steel sheeting requiring higher electricity consumption for the forming and hot-dip galvanisation processes.

Wonderglas GC and Webglas GC roof sheeting have slightly lower embodied energy during the usage stage shown in Figure 4.8. This is owing to all sheeting using the same quantities of steel battens, screws and electricity required during the installation. The main difference is intrinsically contributed by the fuel consumption during the installation as the Wonderglas GC are Webglas GC lighter than the galvanised steel sheeting. As a results, the embodied energy for the fuel consumption of the three sheeting are 1.66, 2.29 and 2.62 MJ_{eq} respectively which equals to a reduction of 37% and 13% when using the Wonder GC and Webglas GC sheeting.

However, the end-of-life or the disposal life cycle stage of the galvanised steel sheeting performs better than Wonderglas GC and Webglas GC. This was because an assumption was made that 70% of the steel could be recycled[30], whereas Wonderglas GC and Webglas GC sheeting were assumed as 100% landfill[31]. Therefore, the embodied energy of the galvanised steel roof sheet at this stage is -44 MJ_{eq}. This indicates that energy is saved from the recycling process by 44 MJ_{eq}.

Wonderglas GC and Webglas GC roof sheeting gain an embodied energy value of -4 and -3.7 MJ_{eq} respectively. These two negative results indicate that energy is gained back from the recycling process by 4 MJ_{eq} and 3.7 MJ_{eq} respectively from the 70% recycling for the galvanised steel battens and steel screws and 100% landfill process for fibre composite sheeting.

Overall, the total embodied energy results for the life cycle of the galvanised steel roof sheeting is 180 MJ_{eq} per square metre. The embodied energy of Wonderglas GC and Webglas GC roof sheeting are 79 and 102 MJ_{eq} per square metre respectively. Figure 4.8 shows that the embodied energy for the life cycle of a square metre of roof sheeting can be significantly reduced by 56% and 43% when it is fabricated from the Wonderglas GC and Webglas GC sheeting respectively instead of the galvanised steel roof sheeting. This dramatic reduction occurs at the material stage and is due to the embodied energy being 71% and 55% higher for the galvanised steel sheeting than that of Wonderglas GC and Webglas GC roof sheeting respectively.

Figure 4.9 presents the embodied energy results from the environmental aspect of greenhouse gas emissions. These results were assessed by the IPCC GWP 100a version 1.00 (IPCC1.00) method as presented in Section 4.2.2. The embodied energy of the roof sheeting at the material life cycle stage are 8 kg CO_{2eq} per square metre for the galvanised steel sheeting, 1.4 kg CO_{2eq} per square metre for the Wonderglas GC sheeting and 2.2 kg CO_{2eq} per square metre for Webglas GC sheeting. The difference between the two materials and the galvanised steel sheeting equate to a reduction in greenhouse gas emissions of 82% and 73% respectively. This is due to the fact that a relatively high amount of energy is required during the steel extraction process. Therefore, the emissions of greenhouse gases are subsequently higher.

---

[30] The assumptions were made based on the household waste data from Australian data 2007 library of the Life Cycle Assessment software as shown in Appendix C.

[31] The assumptions were made based on the provided input data from Ampelite Pty Ltd.

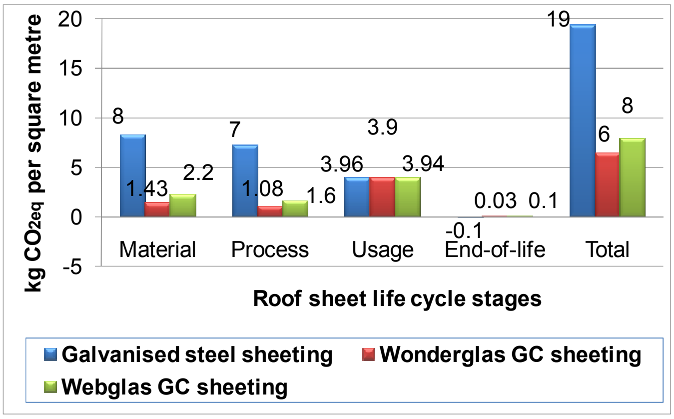


Figure 4.9: Comparison of greenhouse gas emission results for a square metre of the three roof sheeting

Wonderglas GC and Webglas GC roof sheeting were also found to have less greenhouse gas emissions than the galvanised steel sheeting at the manufacturing process and usage stages in Figure 4.9. The manufacturing process is reduced by 85% and 77% respectively when using the two gel coated polyester sheeting. This was owing to the metal forming and galvanised process consuming higher electricity.

During the installation, Wonderglas GC and Webglas GC roof sheeting have slightly lower embodied energy during the usage stage in Figure 4.9. This is due to all sheeting using the same quantities of steel battens, screws and electricity during installation. The main difference is the fuel consumption used during installation, as the Wonderglas GC and Webglas GC sheeting are lighter than the galvanised steel sheeting. Therefore, less fuel is required to be used during transportation. As a result, the greenhouse gas emissions for the fuel consumption of the three different sheeting materials are 0.1, 0.14 and 0.16 kg CO_{2eq} respectively which equates to a reduction of 38% and 13% when using the Wonder GC and Webglas GC sheeting.

Nevertheless, the shortcoming of the two gel coated polyester sheeting are found in their end-of-life or disposal life cycle stage where the galvanised steel sheeting has a better performance. This was because an assumption was made that 70% of the steel could be recycled[32], whereas the fibre composite roof sheets were assumed as 100% landfill[33]. Therefore, the embodied energy for the Wonderglas GC and Webglas GC roof sheeting at this stage gain 0.03 and 0.1 kg CO_{2eq} respectively. Whilst, the galvanised steel roof

[32] The assumptions were made based on the household waste data from Australian data 2007 library of the Life Cycle Assessment software. The steel is assumed to be recycled at 70% whereas 100% is assumed for the fibre composites.

[33] The assumptions were made based on the provided input data of Ampelite Pty Ltd.

sheeting produced an embodied energy value of -0.1 kg CO_{2eq} which indicates that kg CO_{2eq} is reduced by 0.1 kg as a result of the recycling process.

Overall, the total embodied energy results for the life cycle of the galvanised steel sheeting was 19 kg CO_{2eq} per square metre. The embodied energy of Wonderglas GC and Webglas GC roof sheeting were 6 and 8 kg CO_{2eq} per square metre respectively. Figure 4.9 shows that the embodied energy for the life cycle of a square metre roof sheet can be reduced by 68% and 58% when it is fabricated from Wonderglas GC and Webglas GC roof sheeting respectively instead of the galvanised steel sheeting. This dramatic reduction occurs at the material stage and is due to the embodied energy being 82% and 73% higher for the galvanised steel roof sheeting than that of the two gel coated polyester roof sheets.

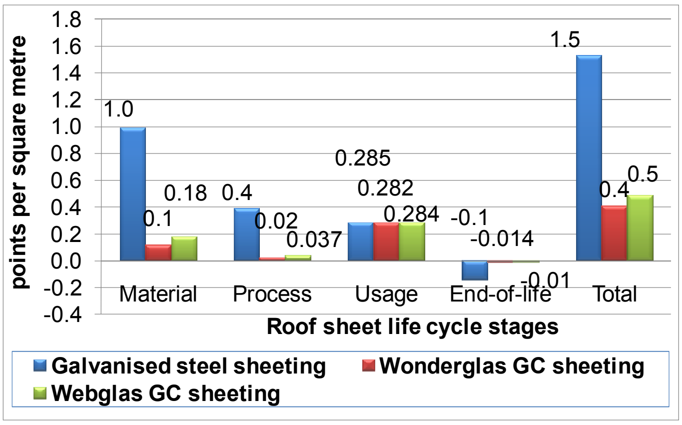


Figure 4.10: Comparison of total environmental impact results for a square metre of the three roof sheeting.

Figure 4.10 presents the total environmental impacts results using the Eco-Indicator 99 H/A version 2.03 method as stated in Section 4.2.2. This is a full Life Cycle Assessment analysis as it calculates the environmental impacts that have an effect towards human health, the ecosystem quality and resource use. The calculation takes into account all emission substances such as airbourne and waterbourne emissions. These impacts are then calculated into a single score which is expressed in a unit of points.

The total environmental impacts results at the material life cycle stage are 1 point per square metre for the galvanised steel sheeting whereby 0.1 and 0.18 points per square metre were found in Wonderglas GC and Webglas GC roof sheeting. These 90% and 82% reduction respectively are due to the fact that a relatively high amount of energy is required during the steel extraction process. Therefore, a large amount of emission substances are emitted, which subsequently cause high environmental impacts.

Wonderglas GC and Webglas GC roof sheeting were found to have less environmental impacts than the galvanised steel sheeting at the manufacturing process and usage stages in Figure 4.10. The environmental impacts are reduced by 99% and 91% respectively during the manufacturing process. This significant reduction is due to the galvanisation process consuming electricity, requiring additional Zinc and also emitting a number of metallic airbourne emissions such as zinc, iron and cadmium[34].

During the installation, Wonderglas GC and Webglas GC roof sheeting have slightly lower environmental impact during the usage stage in Figure 4.10. This is owing to all sheeting used the same quantities of the steel battens, screws and electricity required during the installation. The main difference is intrinsically contributed by the fuel consumption during the installation as the Wonderglas GC and Webglas GC sheeting are lighter than the galvanised steel sheeting. As a result, the greenhouse gas emissions for the fuel consumption of the three sheeting are 0.005, 0.0068 and 0.0078 point respectively which equals to the reduction of 36% and 13% when using the Wonder GC and Webglas GC sheeting.

Nevertheless, the shortcoming of the two gel coated polyester sheeting are found in their end-of-life or the disposal stage. The galvanised steel sheeting performs better than Wonderglas GC and Webglas GC roof sheeting. This was because an assumption was made that 70% of the steel could be recycled[35], whereas the fibre composite roof sheets were assumed as 100% landfill[36]. Therefore, the embodied energy for the galvanised steel roof sheet at this stage is -0.1 points. This indicates that energy is gained back from the recycling process by -0.1 point. Wonderglas GC and Webglas GC roof sheeting saved embodied energy by -0.014 point and -0.01 point from the recycling process of the steel battens and screws.

Overall, the total environmental impacts results for the life cycle of the galvanised steel roof sheet is 1.5 points per square metre, compared to the total environmental impacts of Wonderglas GC and Webglas GC roof sheeting which are 0.4 and 0.5 points per square metre. Figure 4.10 shows that the total environmental impacts for the life cycle of a square metre of roof sheeting can be reduced by 73% and 67% when it is fabricated from the Wonderglas GC and Webglas GC instead of the galvanised steel. This substantial reduction occurs at the material stage and is due to the total environmental impacts being 90% and 82% higher for the galvanised steel roof sheet than that of the fibre composites.

According to Figures 4.8 to 4.10, a square metre of roof sheeting which is manufactured from the gel coated polyester of Ampelite Pty Ltd has a significantly lower embodied energy value than the one that was made from galvanised steel. The gained benefits in making roof sheeting out of the gel coated polyester rather than galvanised steel sheeting are described in the following three points.

---

[34] The emissions are based on the ETH-ESU 96 database from the Simapro software as shown in Appendix C.

[35] The assumptions were made based on the household waste data from Australian data 2007 library of the Life Cycle Assessment software as shown in Appendix C.

[36] The assumptions were made based on the provided input data of Ampelite Pty Ltd.

- In terms of the energy consumption, a roof sheet that is made from Wonderglas GC and Webglas GC can reduce its energy consumption during its life cycle by up to 56% and 43% respectively.
- A roof sheet that is made from Wonderglas GC and Webglas GC can reduce the amount of greenhouse gases emitted into the atmosphere by 68% and 58% respectively during its life cycle.
- A roof sheet that is made from Wonderglas GC and Webglas GC an reduce the total environmental impacts that can effect human health, the ecosystem quality and resource use by 73% and 67% respectively.

On the whole, these benefits are mainly gained during the material stage of the roof sheeting life cycle. This is because the fibre composites used significantly less extraction energy and electricity during the manufacturing process, as well as fuel from the transportation methods than one made from galvanised steel sheeting. However, the gel coated polyester of the fibre composite roof sheet has a higher embodied energy than the galvanised steel sheeting at the end-of-life stage due to the different disposal options.

4.6 Conclusion

This chapter presented the cradle-to-factory and the cradle-to-grave analyses which assessed the embodied energy for the raw materials of Wonderglas GC and the roof sheeting's that are made from Wonderglas GC, Webglas GC and galvanised steel. The methodology overview was presented by defining the scopes and assumptions of the input data which was required for the calculation of the embodied energy analysis. The Life Cycle Assessment method was selected to calculate the embodied energy of the raw materials and the three different roof sheets. This assessment produced the embodied energy and total environmental impacts results. They were the primary energy consumption, the greenhouse gas emissions and the total environmental impacts.

These results were expressed in a unit of MJ_{eq}, kg CO_{2eq} and points respectively. The MJ_{eq} and kg CO_{2eq} results were the generic embodied energy values, however these two units are only considered the primary energy consumptions and the greenhouse gas emissions. Therefore, the points results were generated from the full Life Cycle Assessment which covers all emission substances that can affect the environment in terms of human health, ecosystem and resource (fossil fuels and mineral) use. Thereafter, the description of the raw materials and the three different roof sheet materials were specified. The input data of the cradle-to-factory and the cradle-to-grave analyses was determined on the basis of the scopes, assumptions and descriptions.

The embodied energy results of the cradle-to-factory analysis demonstrated that the raw materials of a kilogram of Wonderglas GC gives the primary energy source by 12 MJ_{eq}, reduces the greenhouse gas by 0.6 kg CO_{2eq} and has 0.05 points of the total environmental impact. These results are contributed by 62% to 71% from the raw material extraction and 29% to 38% from the transportation of the raw materials. The suggestions for reducing the embodied energy of the fibre composite were given in two different directions. They were using low embodied energy raw materials and/or choosing suppliers that use a delivery transportation method that has a low embodied energy.

Subsequently, a hot spots analysis was performed to identify the raw materials or the suppliers that have significantly high embodied energy. Whilst, the embodied energy of the raw materials (M1), (M5) and (M4) are significantly higher than other raw materials, the transportation of the raw materials (M1), (M5) and (M8) are also substantially high. Some recommendations were given such as change to local manufacturers and avoiding as practically as possible the use of road transportation by leaning towards water and rail transportation.

The embodied energy results for the life cycle of a square metre of roof sheeting were assessed using the cradle-to-grave analysis. The roof sheeting was made from Wonderglas GC, Webglas GC and galvanised steel. These results illustrated that the embodied energy of the fibre composite roof sheeting is considerably lower than the galvanised steel roof sheet. This is owing to the significant reduction in energy needed to extract the raw material during the material stage. The manufacturing process of the steel galvanisation consumes higher energy than the pultrusion process. Moreover, the fibre composite sheeting is lighter than the galvanised steel sheeting, therefore, the fuel consumption to transport the material is proportionally reduced during the installation phase of the usage stage. These advantages largely outweigh the disadvantages of utilising fibre composites which have a higher embodied energy value during the end-of-life stage.

The total embodied energy results of the three roof sheet life cycles revealed that:

- A square metre of roof that is made from Wonderglas GC and Webglas GC sheeting consume 56% and 43% less energy during their life cycle.
- A square metre of roof that is made from Wonderglas GC and Webglas GC sheeting emit 68% and 58% less greenhouse gases during their life cycles compared to a galvanised steel roof sheet.
- A square metre of roof that is made from Wonderglas GC and Webglas GC sheeting have an environmental impact which is 73% and 67% less than that of a galvanised steel roof sheet. This equates to a lessening on the effects towards human health, the ecosystem quality and resource use during their life cycle.

CHAPTER 5

MUSTANG MARINE AUSTRALIA PTY LTD – EMBODIED ENERGY OF POWERBOAT HULL

5.1 Introduction

A hull is an important element of a motor vessel or powerboat as it determines efficiency and buoyancy of the powerboat, which can travel at high speeds for recreation and sports purposes as shown in Figure 5.1. Traditionally, a variety of materials can be used to build a powerboat hull such as timber, steel and aluminium. This is due to their suitable mechanical and physical properties such as stiffness, lightness and corrosive resistance. Alternatively, Mustang Marine Australia Pty Ltd manufactures a moulded fibreglass hull or Mustang 430 powerboat hull that has a "10 year structurally hull warranty"[37] . A hull made of fibreglass is extremely popular, as a more efficient design is achievable, no resurfacing is required and the shape of the hull is more consistent[34]. Mustang 430 powerboat hull is a hand lamination process by using the basic moulding process as illustrated in Figure 5.2. This process comprises of five main steps, namely mould preparation, application of coloured gelcoat, application of the tie layer (use vinyl ester resin) and main laminate, installation of plywood bulk heads and the installation of foam barrier cores and laminates[34]. Generally, the material selection for a powerboat hull depends on the budgets and extended usage. Mustang 430 powerboat hull does have some physical and economical advantages over the traditional material hull. However, in terms of their environmental performance, it is not so clear and therefore this project was aimed to quantify the embodied energy of Mustang 430 powerboat hull.

Figure 5.1: A powerboat hull[35].

[37] http://www.mustangmarine.com.au

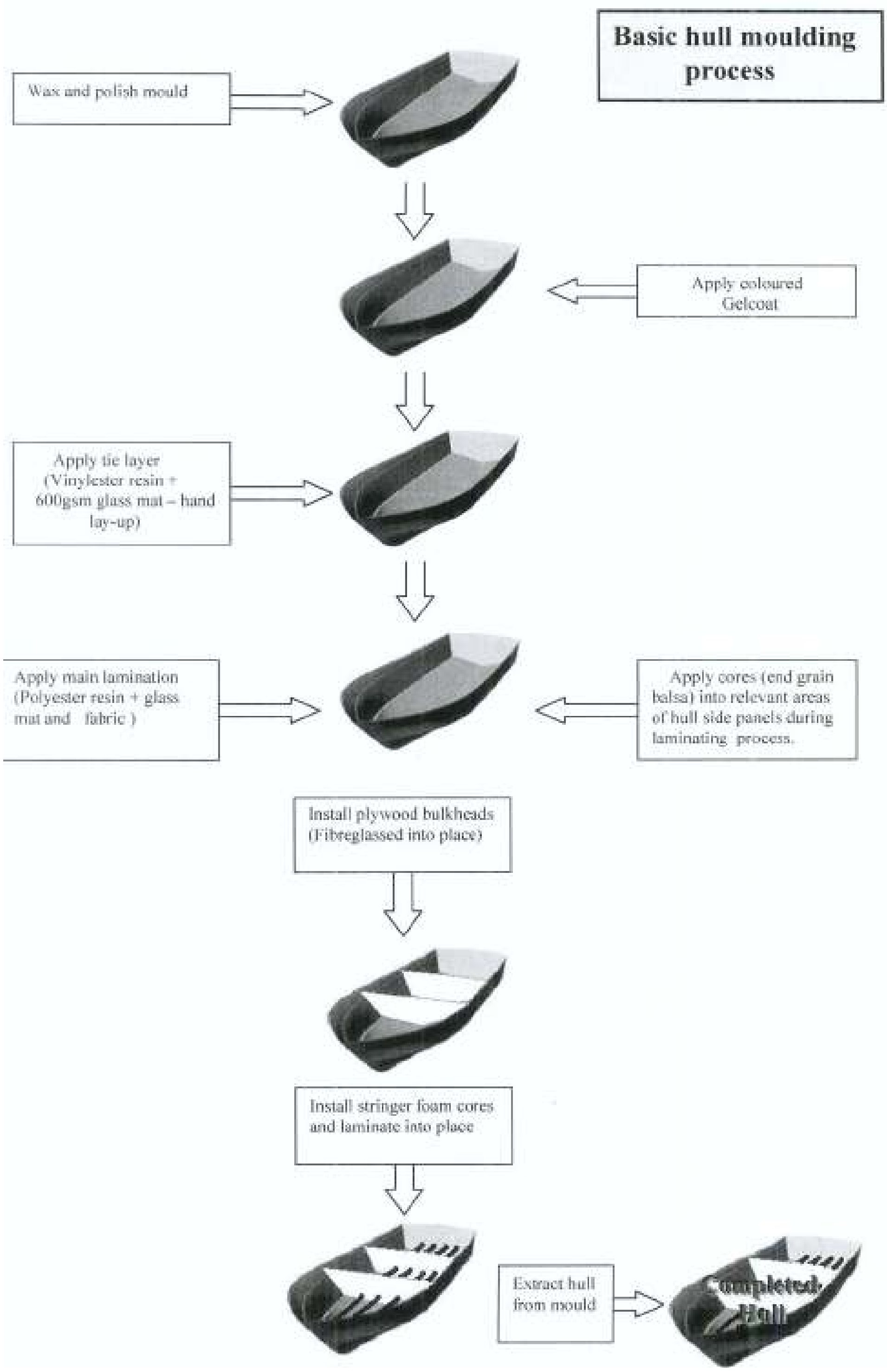


Figure 5.2: A basic hull moulding process.[38]

To quantify the environmental impact, many environmental assessment methods have been developed including the embodied energy and Life Cycle Assessment analysis.

---

[38] www.mustangmarine.com.au

Therefore, this chapter aims to assess the embodied energy and the environmental impact of the raw materials that are used to make a kilogram of Mustang 430 powerboat hull. Moreover, the embodied energy analysis is used to compare a powerboat hull made from two different materials which are the moulded fibreglass and aluminium. Life Cycle Assessment is used as a tool to calculate the embodied energy of a kilogram of moulded fibreglass and the two different powerboat hull materials.

Cradle-to-factory analysis[39] is used in this chapter to determine the embodied energy and the total environmental impacts of the raw materials required to make a kilogram of the moulded fibreglass. This material is manufactured by Mustang Marine Australia Pty Ltd to build Mustang 430 powerboat hull. In addition, cradle-to-grave analysis is employed to compare the embodied energy and the total environmental impacts of the life cycle of powerboat hulls, which are made from moulded fibreglass and aluminium. Theoretically, cradle-to-grave analysis is an assessment of a product life cycle including raw material extraction, manufacturing process, usage, transportation and end-of-life.

The outline of this chapter is as follows:

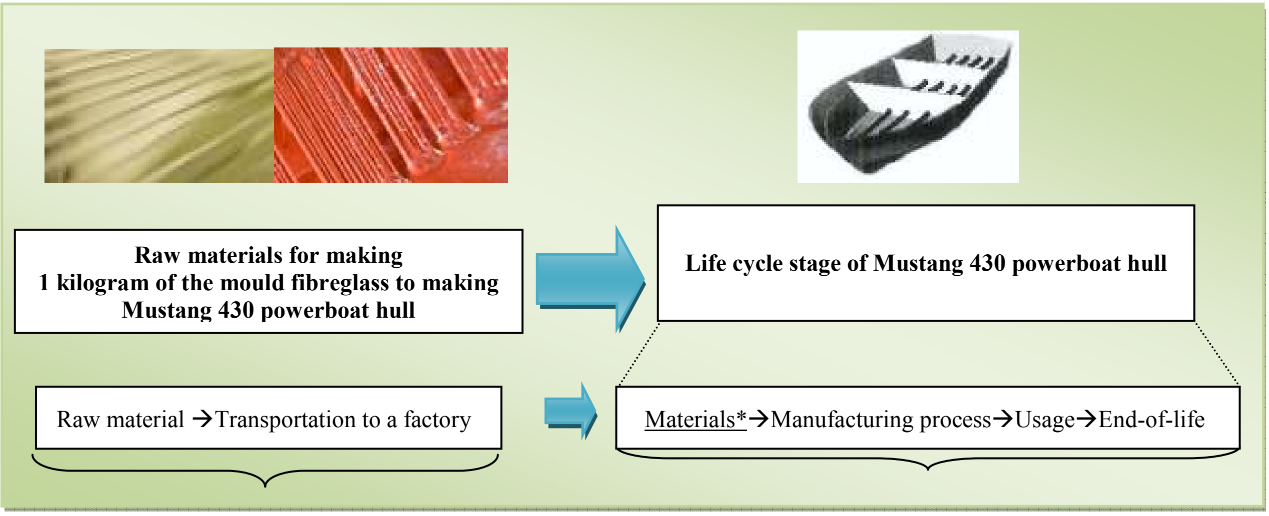
- Methodology overview of the cradle-to-factory and the cradle-to-grave analyses
- General scopes and assumptions of the analyses
- Description of a kilogram of the moulded fibreglass
- Description of the powerboat hulls that are made from the moulded fibreglass and aluminium
- Input data of the cradle-to-factory and the cradle-to-grave analyses
- Cradle-to-factory results and discussion: the embodied energy of the raw materials require to make a kilogram of the moulded fibreglass
- Cradle-to-grave results and discussion: the comparison between a finished powerboat hull that is made from moulded fibreglass and one made from aluminium.
- Conclusion is drawn in the last section of the chapter

[39] Technically, the cradle-to-factory (gate) analysis is commonly defined as "an assessment of a partial product life cycle from manufacture ('cradle') to the factory gate before it is transported to the consumer" (Reference: Moreno, A., 2008, The DEPUIS HANDBOOK Chapter 4: Methodology of Life Cycle Assessment, Accessed: October 2009, http://www.depuis.enea.it/dvd/website.html). However, cradle-to-factory analysis in this project is specified as the embodied energy incurred during the raw material extraction and the transportation from suppliers to manufacturers.

5.2 Methodology Overview

5.2.1 Embodied energy analysis

In this study, the embodied energy analysis of a powerboat hull comprises of the cradle-to-factory and the cradle-to-grave analyses as shown in Figure 5.3. These analyses employ the Life Cycle Assessment method to assess the environmental impacts of all life cycle stages as shown in Figure 5.3. The methodology of these two methods is described briefly as follows.



CRADLE-TO-FACTORY[40] CRADLE-TO-GRAVE

Figure 5.3: Scopes of the cradle-to-factory and the cradle-to-grave analyses.

The methodology of these two analyses is described briefly as follows. Firstly, the cradle-to-factory analysis assesses the embodied energy in making 1 kilogram of the mould fibreglass as presented in the left portion of Figure 5.3. This analysis focuses on two main embodied energy sources. They are the raw material extraction and the transportation of raw materials from the supplier to a factory, i.e. Mustang Marine Australia Pty Ltd. The asterisk sign next to the word 'Materials' in Figure 5.3 indicates that the embodied energy result from this analysis will be used as the input data for the materials stage in the cradle-to-grave analysis.

Secondly, the cradle-to-grave analysis as shown in Figure 5.3 calculates the life cycle of Mustang 430 powerboat hull which is assumed to have a life span of 30 years. For comparison purposes this analysis technique is also performed on an aluminium hull with the same weight. The life cycle stages of these products are presented on the right hand side of Figure 5.3 where:

[40] The resin photo was taken from www.exelcomposites.com

- The materials stage is the total raw materials that are used in making the powerboat hulls;
- The manufacturing process stage comprises the processes involved in making the powerboat hulls.
- The usage stage consists of the activities that occur after the powerboat hull is manufactured i.e. the installation and maintenance activities, until the product is disposed of. In this case, the usage period is 30 years where the distribution and the resurfacing activities are considered.
- The end-of-life stage is the disposal scenario which includes the transportation of the powerboat hulls to the disposal site and the disposal process.

Finally, the embodied energy and the total environmental results from the cradle-to-factory analysis are discussed and the hot spots identified. For this project a hot spot is defined as the raw materials and/or suppliers which have a high contribution to the embodied energy and the total environmental results. The hot spots analysis was conducted in order to make further suggestions in order to minimise or eliminate the identified raw materials and/or suppliers. Subsequently, the embodied energy results from the cradle-to-grave analysis of Mustang 430 powerboat hull are analysed and compared with the life cycle of the aluminium powerboat hull.

5.2.2 Scopes and assumptions of the embodied energy analysis

This section presents Tables 5.1 to 5.3 to clarify the scopes and assumptions that were made for the cradle-to factory and the cradle-to-grave analyses. Tables 5.1 and 5.2 provide the main scope of the cradle-to-factory analysis which focuses on quantifying the embodied energy of the raw materials in making a kilogram of the moulded fibreglass. Table 5.2 illustrates the raw materials that are considered as the input data for the raw materials of the moulded fibreglass. Referring to the raw materials of the moulded process as presented in Figure 5.2, most of the raw materials in Figure 5.2 are included except the polyurethane foam and plywood[41]. These two excluded materials are however included in the material stage of the cradle-to-grave analysis which assess the embodied energy of Mustang 430 powerboat hull life cycle.

Therefore, the scopes of the input data that are associated with the raw material extraction and their transportation are given in Table 5.2. Furthermore, the table shows the data sources that are used to make the assumptions for the input data of the cradle-to-factory analysis. Overall, the input data in terms of the quantities and the types of materials and transportation were provided by Mustang Marine Australia Pty Ltd. The rest of the data was obtained using further literature reviews and the libraries from the database of the LCA software, SimaPro 7.1.8. For instance, the input data for the amount of raw material was based on

[41] According to Mustang Marine Australia Pty Ltd, the polyurethane foam and plywood are used as structure member core and bulkheads.

the information from the Material Safety Datasheets (MSDs) which were provided by Mustang Marine Australia Pty Ltd. The material types were assumed using the Australian Data 2007 (AU) and the IDEMAT2001 libraries whereby the distance of the transportation for raw materials was found using the online maps provided by Google.

Layer	Weight (kg)	Assumption
Mould fibreglass	3,565	Hull laminate which include the fibreglass laminate and end grain balsa
Polyurethane foam	45	These materials are included as the material stage of the powerboat hull life cycle.
Plywood	170	

Table 5.1: Summary of materials used in making Mustang 430 powerboat hull

<table>
<tr><th colspan="7">CRADLE-TO-FACTORY</th></tr>
<tr><td colspan="7">Scope: To quantify the embodied energy of the raw materials in making a kilogram of the mould fibreglass.</td></tr>
<tr><td>Input data</td><td colspan="6">Amount of the raw materials used in making 1 kilogram of the mould fibreglass.</td></tr>
<tr><td rowspan="2">Material life cycle stage</td><td rowspan="2">Scopes and assumptions</td><td colspan="5">Data sources</td></tr>
<tr><td>MM</td><td>LR</td><td>AU</td><td>DA</td><td>ID</td></tr>
<tr><td rowspan="2">Raw material extraction</td><td>Amount of raw materials (kg)</td><td>✓</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Material types</td><td>✓(MSDs)</td><td>✓</td><td>✓</td><td></td><td>✓</td></tr>
<tr><td rowspan="3">Transportation of raw materials:
From: Suppliers
To: Mustang Marine Australia Pty Ltd (Queensland)</td><td>The locations of suppliers</td><td>✓</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Distance (km): Measure using the online maps</td><td></td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>Transportation types</td><td>✓</td><td></td><td>✓</td><td></td><td></td></tr>
</table>

Note: Mustang Marine Australia Pty Ltd (MM), Literature review (LR), the 'Australia data 2007'(AU), the 'Data archive' (DA), and the 'IDEMAT2001'(ID) libraries are the databases from the SimaPro 7.1.8 software.

Table 5.2: Scopes and assumptions of cradle-to-factory analysis for the moulded fibreglass

Similarly, Table 5.3 presents the scopes of the cradle-to-grave analysis for the life cycle of the two powerboat hulls during their life span of 30 years. The input data for each life cycle stage were assumed in terms of the quantities and types which are based on the data sources as shown in the table.

It is worth highlighting the assumption for the material stage of Mustang 430 powerboat hull life cycle in Table 5.3. The material stage has two embodied energy sources. They are the raw material extraction and the transportation of those materials. In this material stage, the materials for making a powerboat hull include the moulded fibreglass, polyurethane foam and plywood.

Thus, the calculation of the embodied energy at this stage is performed in two steps. The first step is to calculate the embodied energy for the total amount of moulded fibreglass directly from the embodied energy results of the cradle-to-factory analysis. The second step is to calculate the embodied energy of the polyurethane foam and plywood based on their input data of their raw material extraction and the transportation. The calculation for the first step is carried out by multiplying the embodied energy results from the cradle-to-factory analysis with 3,565 kg per powerboat hull.

For instance, the embodied energy result for the raw material extraction from the cradle-to-factory analysis is 26 MJ_{eq} per kg and the weight of moulded fibreglass is 3,565 kg per powerboat hull. Therefore, the embodied energy result for the material stage in this cradle-to-grave analysis is:

$$26\ MJ_{eq} \text{ per kg} \times 3{,}565 \text{ kg per powerboat hull} = 96{,}690\ MJ_{eq} \text{ per powerboat hull}$$

CRADLE-TO-GRAVE						
Scope: To analyse the embodied energy for the life cycle for a powerboat hull that is made from mould fibreglass and aluminium during the life span of 30 years.						
Life cycle stages of the powerboat hulls	**Scopes and assumptions**	**Data sources**				
		MM	LR	AU	DA	ID
Material stage: *Input data for Amount of the raw materials per 1 powerboat hull from the main two embodied energy sources:* Raw material extraction and transportation of raw materials: *From:* A Supplier *To:* Mustang Marine Australia Pty Ltd	***Mustang 430 powerboat hull:*** **Material type:**					
	- *Mould fibreglass:* 3,565 kg per hull Multiply the embodied energy results from the cradle-to-factory analysis which is produced in the unit of per kg with 3,565 kg per hull.	✓	✓	✓		✓
	-*Polyurethane foam:* 45 kg per hull	✓		✓		✓
	-*Plywood:* 170 kg per hull	✓	✓	✓		
	Aluminium powerboat hull: **Material type:**					
	- *Aluminium series 5086:* 3,760 kg per hull (the weight is the same as the total weight of the finished mould fibreglass powerboat hull)		✓	✓		
	Distance*: From Wollongong. Use the online map to measure the distance (km)			✓		
	By*: Articulated truck for freight			✓		
Manufacturing process: *Input data*	***Mustang 430*** *powerboat hull:* **Energy type:** Electricity in Queensland			✓		
	Amount: Total Electricity consumption: 1,567 kWh per hull	✓				
	Aluminium powerboat hull:* **Process type:**					
	80% Cold-transforming process: 3,008 kg		✓	✓		
	20% Extrusion process: 752 kg		✓	✓	✓	
Usage: Distribution *Input data* *From:* Mustang Marine Australia Pty Ltd *To:* A customer	*Both powerboat hulls:* **Distance***: 200km **By***: Light commercial vehicle			✓		
Usage: *Input data* Maintenance	*Both powerboat hulls:* No maintenance is required.	✓	✓			
End-of-life: *Input data* Disposal transportation *From:* A customer *To:* A disposal site	*Both powerboat hulls:* **Distance***: 200km **By***: Light commercial vehicle			✓		
End-of-life: *Input data* Disposal scenarios	*Both powerboat hulls:* **Household waste**:			✓		
	100% landfill for mould fibreglass material	✓		✓		
	65% recycling for aluminium			✓		

*Note: *Arbitrary assumption is used a standard value for the 'Composites: Calculating their Embodied Energy Study' where 200 km was suggested by one of the participant composite company.*
Mustang Marine Australia Pty Ltd (MM), Literature review (LR), the 'Australia data 2007'(AU), the 'Data archive' (DA) and the 'IDEMAT2001'(ID) libraries are the databases from the SimaPro 7.1.8 software.

Table 5.3: Scopes and assumptions of the cradle-to-grave analysis for Mustang 430 powerboat hull

In addition, certain input data for the life cycle of the two powerboat hulls was assumed arbitrarily. This is because there was no input data available as the data will vary depending on the situation. However, it is essential to assume the same value for transportation in order to make a fair comparison. Therefore, 200 kilometres and a light commercial vehicle were assumed for the installation and the disposal transportation for both powerboat hulls. The transportation for the resurfacing of the aluminium hull was also assumed as 60 kilometres. Moreover, the 200 kilometre distance was based on the input data that was designated by one of the participant companies in this 'Composites: Calculating their Embodied Energy' Study. Table 5.4 is given to clarify scopes and the assumptions of the embodied energy calculation tool which was selected for the cradle-to-factory and the cradle-to-grave analyses.

<table>
<tr><th colspan="5">EMBODIED ENERGY CALCULATION TOOL</th></tr>
<tr><th>Embodied Energy Analysis</th><th colspan="4">Scopes and Assumptions</th></tr>
<tr><td>Embodied energy assessment tool</td><td colspan="4">The Life Cycle Impact Assessment methods from the LCA software, SimaPro 7.1.8 software.</td></tr>
<tr><td>Selection of the Life Cycle Impact Assessment methods</td><td colspan="4">The selection of these methods was based on the generic embodied energy analysis which is often based on the input-output model that is used to quantify the primary energy sources and often expressed in MJ and in kg of CO_2 units. In addition, as the two values from the Cumulative energy demand version 1.04 and the IPCC GWP 100a version 1.00 methods only represent the embodied energy in terms of the primary energy consumption and the impacts from the climate change respectively. Therefore, the points value is also given. This value is calculated from Life Cycle Assessment which considers the impacts on human health, the ecosystem quality and resource use. The points value is calculated from the Eco-Indicator 99 H/A version 2.03 method.</td></tr>
<tr><th colspan="5">LIFE CYCLE IMPACT ASSESSMENT METHODS</th></tr>
<tr><th rowspan="2">Method</th><th rowspan="2">Calculation Approach and unit</th><th colspan="3">Embodied Energy Results</th></tr>
<tr><th>Cradle-to-factory</th><th>Cradle-to-grave</th><th>Amount of conventional air pollutions</th></tr>
<tr><td>Cumulative energy demand version 1.04</td><td>Calculation: Calculates the embodied energy in terms of the consumption of the primary energy sources such as fossil fuels, minerals, renewable energy.
Unit: MJ_{eq}</td><td>MJ_{eq} per kg</td><td>MJ_{eq} per powerboat hull</td><td rowspan="3">Carbon monoxide (CO)
Carbon dioxide (CO_2)
Nitrogen dioxide (NO_2)
Sulphur dioxide (SO_2)
Unspecified particulate
Volatile organic compounds (VOC)</td></tr>
<tr><td>IPCC GWP 100a version 1.00</td><td>Calculation: Calculates the greenhouse gas emissions which impact the global warming.
Unit: kg CO_{2eq}</td><td>kg CO_{2eq} per kg</td><td>kg CO_{2eq} per powerboat hull</td></tr>
<tr><td>Eco-Indicator 99 H/A version 2.03</td><td>Calculation: calculates as the environmental performance indicator as a single score. This is a comprehensive Life Cycle Assessment analysis which considers human health, the ecosystem quality and resource use impacts.
Unit: points of a single score</td><td>points per kg</td><td>points per powerboat hull</td></tr>
</table>

Table 5.4: Scopes and assumptions for the embodied energy calculation tools and results

As a result, three Life Cycle Impact Assessment methods from the SimaPro 7.1.8 software were selected as shown in the table. They are the Cumulative Energy Demand version 1.04, the IPCC GWP 100a version 1.00 and the Eco-Indicator 99 H/A version 2.03 methods. Furthermore, Table 5.4 also summarises the calculation approach and the results of the three methods for the cradle-to-factory and the cradle-to-grave analyses. These methods generated the embodied energy and the total environmental impacts results for these analyses in the units of MJ_{eq}, kg CO_{2eq} and points per kg as well as in units of MJ_{eq}, kg CO_{2eq} and points per square metre. Therefore, Figure 5.4 is given to provide additional information to aid in how to interpret these results. Additionally, the amount of six conventional air pollutants as listed in Table 5.4 are given as the total airbourne substances that are emitted during the cradle-to-factory and the cradle-to-grave analyses. The next section presents the material and product description for the cradle-to-factory and the cradle-to-grave analyses.

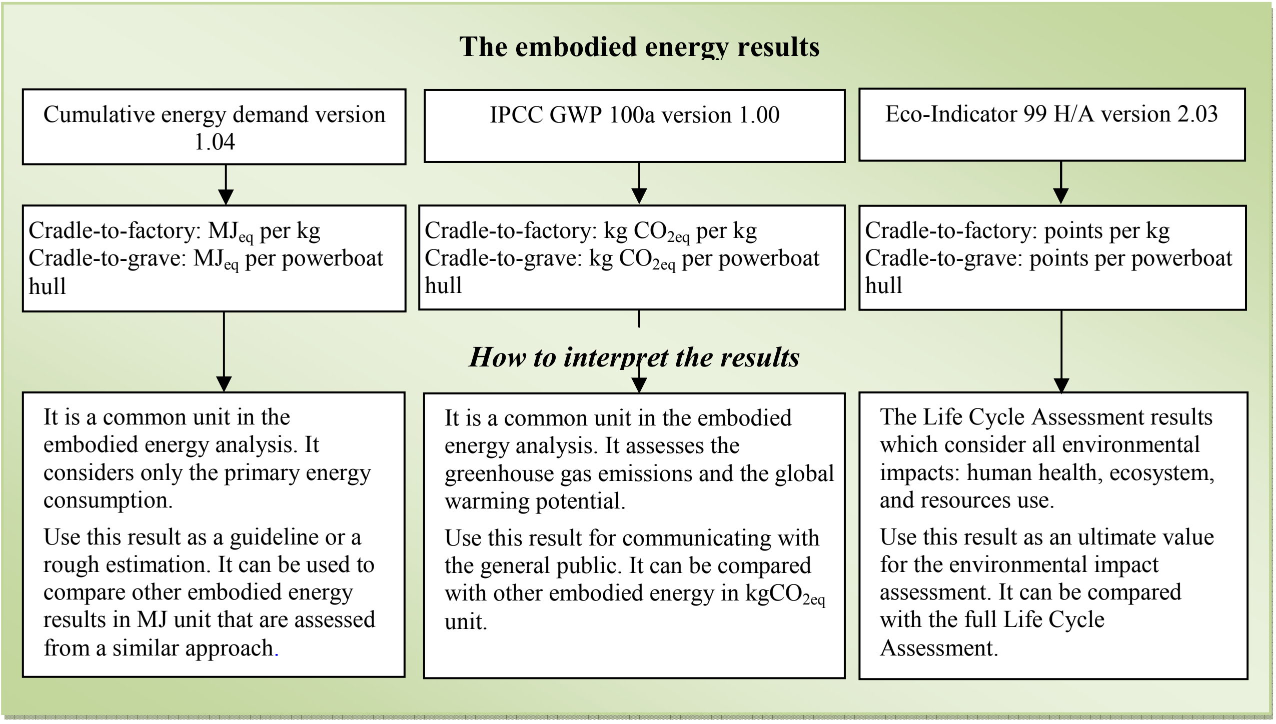


Figure 5.4: How to interpret the embodied energy results

5.3 Material and Product description

5.3.1 Mould fibreglass description

Referring to Table 5.2, the mould fibreglass is another layer that is applied to build Mustang 430 powerboat hull as listed in Table 5.1. The description of the raw materials used in manufacturing of this moulded fibreglass is summarised in Table 5.4. The data in this table is used as a basis of the cradle-to-factory analysis.

Raw material type	List of raw material	Region of supplier	Road and water transportation of raw material: from a supplier to the factory, Mustang Marine Australia Pty Ltd (Must.)
Fibre glass	M3, M6 to M8	Asia and Australia	Supplier → (M_T1) → (M_T2) → Factory *(M3, M6 to M8) (Must.)
End grain balsa	M10	Australia	Supplier → (M10_T1) → Factory *(M10) (Must.)
Resin	M2 and M5	Asia and Australia	Supplier → (M_T1) → Factory *(M3and M5) (Must.) and Supplier → (M_T1) → (M _T2) → Factory *(M2 and M5) (Must.)
Others: **such as catalysts and gel-coat**	M1, M4, M7 and M9	Asia and Australia	Supplier → (M_T1) → Factory, *(M1 and M9) (Must.) and Supplier → (M_T1) → (M_T2) → Factory, *(M4 and M7) (Must.)

Note: The abbreviations of 'M' and "M_T' are provided for the discussion of Figure 6.8.
Raw material types (M), First transportation of the raw material (M_T1), Second transportation of the raw material (M_T2), Third transportation of the raw material (M_T3), Fourth transportation of the raw material (M_T4),
(Road transportation such as a truck) and (Water transportation such as an Australian international shipping)

Table 5.4: Raw materials and the transportation of raw materials in making a kilogram of the mould fibreglass.

Various raw materials constitute the composite material such as fibreglass, plastic resins as well as catalysts, gel-coat and additives as presented in Table 5.4. These raw materials are supplied by ten suppliers from New South Wales, Queensland and Victoria, Australia and two countries in the Asia region. Table 5.4 demonstrates the transportation of the raw materials from suppliers to Mustang Marine Australia Pty Ltd located on the Gold Coast, Queensland which involves road and water transportation. The transportation of the raw materials is presented in the last column of Table 5.4. Additionally, Table 5.4 presents the abbreviations of the raw material type 'M' and its transportation 'M_T' which are provided for later discussion in this chapter. As there are ten suppliers involved in this analysis, M1 to M10 and also M1_T1 to M10_T1 are presented in Table 5.4.

Noticeably, some of the raw materials transported from the supplier to Mustang Marine Australia Pty Ltd require only one transportation method while others need several. The input data of suppliers' addresses for the moulded fibreglass hull was obtained from the list of suppliers and the Material Safety Datasheets that was provided by Mustang Marine Australia Pty Ltd. The one transportation method as shown in Table 5.4 refers to the suppliers from several areas in Australia.

According to this information, most of the raw materials in Australia were assumed to use an articulated truck as their road transportation method from New South Wales to the Gold Coast. For the Asian suppliers as stated in the MSDs, these suppliers were assumed to travel by Australian international shipping from the Asia region to New South Wales, Australia where the suppliers are located. Subsequently, the raw materials were transferred from New South Wales to Mustang Marine Australia Pty Ltd on the Gold Coast.

5.3.2 A powerboat hull description

The cradle-to-grave analysis focuses on assessing the embodied energy of a powerboat hull where Mustang 430 powerboat hull is build using the hull moulding process as demonstrated in Figure 5.2. The raw materials for the powerboat hull consist of the mould fibreglass, polyurethane foam and plywood layers. According to Mustang Marine Australia Pty Ltd, 20 kg is estimated as a waste from the laminate layers which is previously presented in Table 5.2. Therefore the total weight of the finished hull was estimated to be 3,760 kg by subtracting the total weight of the total raw materials used in the moulded fibreglass powerboat hull of 3,780 kg with the 20 kg waste.

For an aluminium powerboat hull, no data was provided by Mustang Marine Australia Pty Ltd. Therefore for the purpose of this study, it was assumed on the weight basis. Generally, both moulded fibreglass and aluminium powerboat hulls have the same weight as the finished powerboat as shown in Figure 5.2. The total weight of aluminium powerboat hull was assumed to be equalled to 3,760 kg which is the total weight finished mould fibreglass powerboat hull. Moreover, 80% of the total weight of the aluminium powerboat hull was assumed to be made from the cold transforming process and 20% of the weight was made from the extrusion process.

5.4 Input Data

The description from previous section was used to identify the value of input data for the cradle-to-grave analysis. This analysis aims to assess the embodied energy of two powerboat hulls made from mould fibreglass and aluminium as presented in Tables 5.5 and 5.6 respectively. This input data was derived from the scopes and the assumptions in Section 5.2.2.

Therefore, the input data of all life cycle stages are presented in terms of a unit, the amount and the 'material/process description' which represents the material and the manufacturing process types.[42]

[42] In relation to this, the data sources for the input data of 'Material/process description' and 'Amount' are also given in the last column of Tables 5.5 and 5.6 for the reference of the database background.

Life cycle stage	Materials/Processes description	Unit	Amount	Data source
Materials:	Moulded fibreglass layers	kg	3,565	Multiply 1 kg results from the cradle-to-factory with 3,565 kg
	Polyurethane foam layer	kg	45*	IDEMAT2001 LCI library
	Plywood layer	kg	170*	Literature review (CPM) [3]
	Articulated truck freight, customisable/AU U: Polyurethane 's supplier transportation: 0.045tonne × 737km	tkm	33.165	Australian data 2007 LCI library
	Articulated truck freight, customisable/AU U: Plywood's supplier transportation: 0.17tonne × 81.2km	tkm	13.804	Australian data 2007 LCI library
Manufacturing process:	High voltage electricity in Queensland for Total energy consumption per hull	kWh	1567*	Australian data 2007 LCI library
Usage: Delivery transportation	Light commercial vehicle	km	200	Australian data 2007 LCI library
End-of-life: Disposal transportation	Light commercial vehicle	km	200	Australian data 2007 LCI library
End-of-life: Household waste	Landfill	%	100*	Australian data 2007 LCI library

*Note: * represent the data that was provided by Mustang Marine Australia Pty Ltd.*

Table 5.5: Input data of Mustang 430 powerboat hull

Life cycle stage	Materials/Processes description	Unit	Amount	Data source
Material	Aluminium hull	kg	3760	Literature review and Australian data 2007 LCI library
Manufacturing process:	Aluminium: cold transforming process	kg	3008	Australian data 2007 LCI library
	Aluminium extrusion	kg	752	Australian data 2007 and Data archive LCI libraries
Usage:	Delivery transportation: Light commercial vehicle	km	200	Australian data 2007 LCI library
Usage: Maintenance	Light commercial vehicle: Return trip to resurfacing at Year 10	km	60	Australian data 2007 LCI library
	Light commercial vehicle: Return trip to resurfacing at Year 20	km	60	Australian data 2007 LCI library
End-of-life: Disposal transportation	Light commercial vehicle: Transportation for landfill is assumed as light commercial vehicle to travel 200km	km	200	Australian data 2007 LCI library
End-of-life: 65% recycling process	Household waste process: Recycling aluminium at 65%	%	100	Australian data 2007 LCI library

Table 5.6: The input data for a aluminium powerboat hull

5.5 Embodied Energy Results

5.5.1 Cradle-to-factory Results and Discussion

The input data from the previous section was employed to conduct the cradle-to-factory analysis. The analysis was carried out by using the Life Cycle Assessment method to assess the embodied energy of the raw materials that are comprised in a kilogram of the mould fibreglass as presented in Figure 5.5.

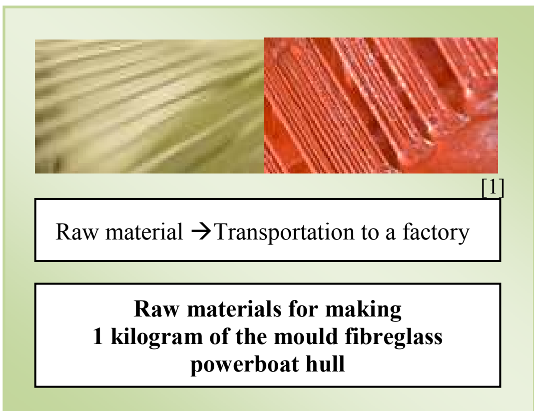
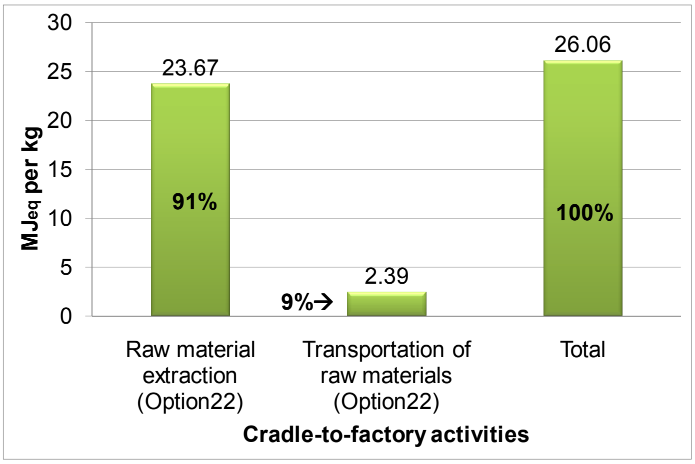
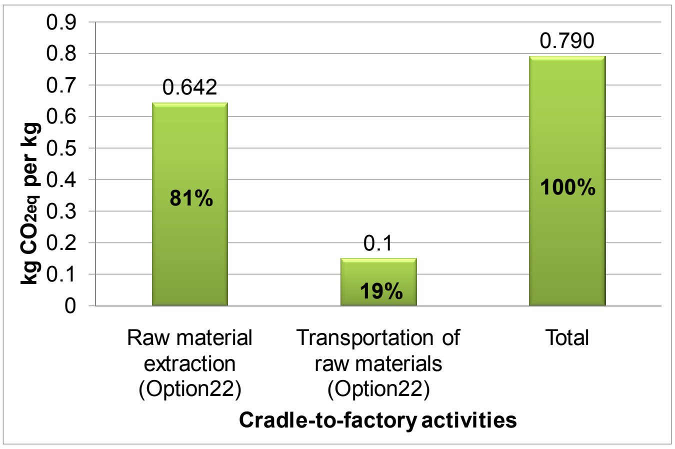


Figure 5.5: The two main embodied energy sources of the cradle-to-factory analysis

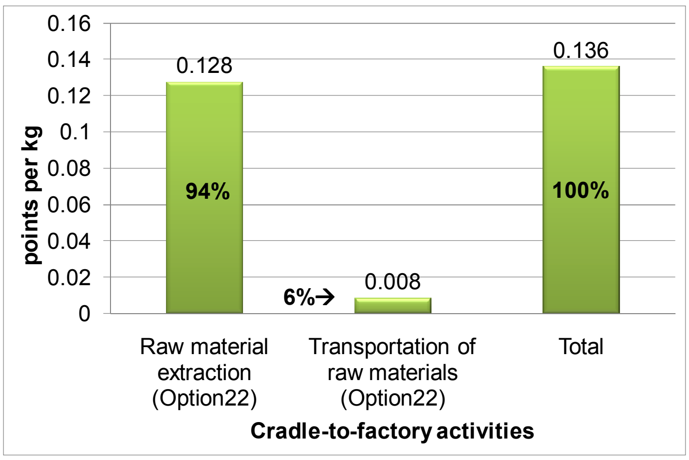
This assessment produced the embodied energy results in three different environmental aspects as presented in Figure 5.6. They are the primary energy consumption, the greenhouse gas emissions and the total environmental impacts or a single score. These results are expressed in a unit of MJ_{eq} per kg, kg CO_{2eq} per kg and points per kg respectively.



(a) Primary energy consumption results



(b) Greenhouse gas emissions results



(c) Total environmental impacts results

Figure 5.6: The cradle-to-factory results for the mould fibreglass of Mustang Marine Australia Pty Ltd.

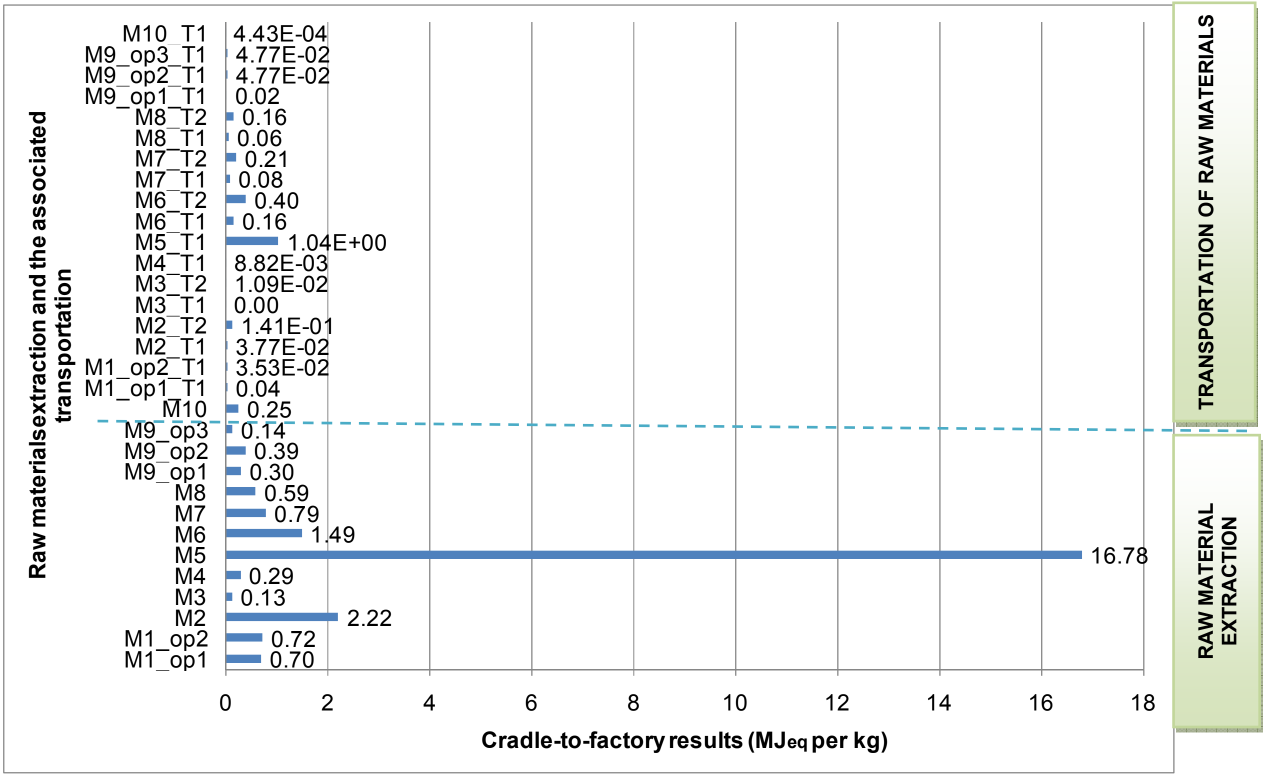
On the whole, the raw materials for a kilogram of mould fibreglass give the total embodied energy results of 26 MJ_{eq}, 0.79 kg CO_{2eq} and the environmental impacts of 0.14 points. These results consist of 81% to 94% from the raw material extraction and 6% to 19% from the transportation of the raw materials as labelled in Figure 5.6. These charts display the results in terms of the raw material extraction and the transportation of the raw materials from suppliers to Mustang Marine Australia Pty Ltd as depicted in Table 5.5. The last bar of the charts gives the total results of the two main embodied energy sources which are the sum of the raw material extraction and the transportation of the raw materials. The total results of these two embodied energy sources are also provided in the last bar of Figures 5.6 (a) to (c).

The distinct contributions of the two embodied energy sources are clearly revealed. The finding suggests that the embodied energy of the mould fibreglass can be reduced in two different directions. The first direction is to reduce the high embodied energy of the raw material extraction by using alternative raw materials with low embodied energy. The second direction is to be selective in choosing the suppliers in order to ensure low embodied energy in their delivery transportation.

Ideally, the first direction would be the best option as it can reduce the embodied energy dramatically by changing some of the raw materials as the raw material extraction actually contributes a large portion in the total embodied energy and the environmental impact result. However, it requires further research and development in finding an alternative or a new raw material which requires further investment of the supporting systems. Therefore, this direction can only be targeted as a long term product development plan. In practice, the second direction would be more attractive as it is a fast and a simple approach which requires only a careful consideration in selecting the suppliers. For instance, the selected suppliers should supply the raw materials that are manufactured locally or require less energy-intensive transportation system for transporting the raw materials.

To enhance the implementation of these suggestions, Figure 5.7 explicitly presents the embodied energy for each raw material and its corresponding transportation method. These results from Figure 5.7 are produced from the detailed input data such as the MSDs and the actual location of the suppliers for all raw materials provided by Mustang Marine Australia Pty Ltd. Figure 5.7 reveals that the embodied energy and the environmental impacts of the mould fiberglass from Mustang Marine Australia Pty Ltd was dominated by the combination of several raw materials which originated from overseas suppliers. As a result, a number of hot spots which are the raw materials or the suppliers that have significantly high values are revealed in Figure 5.7.

In this occasion, the raw material (M5) contributes the most followed by the raw materials (M2) and (M6) whereby the obvious hot spots of the supplier's transportation are the transportations of the raw materials (M5), (M6), (M7) and (M8). Similarly, these higher contributions of the embodied energy for the transportation methods were observed with notable reasons.



Note:Raw material types (M), First transportation of the raw material (M_T1) and Second transportation of the raw material (M_T2)

Figure 5.7: The detailed embodied energy results (MJ_{eq}/kg) of the cradle-to-factory analysis which displays types and transportation of raw materials.

Since these raw materials were imported in high quantities from the Asia region and in different states of Australia, the water and road transportation methods were mainly used. The Australian international shipping was utilised for shipping the raw materials from overseas to New South Wales where the suppliers are located. Subsequently, articulated trucks were used to transport the raw material freight from New South Wales to Mustang Marine Australia Pty Ltd which is located on the Gold Coast, Queensland.

Therefore, this transportation system produced a high embodied energy value in particular from the road transportation which travels over a significantly long distance i.e. the transportation of raw materials (M5_T1), (M6_T2), (M7_T2) and (M8_T2) from New South Wales to the Gold Coast.

Consequently, these hot spots can be minimised and eliminated by examining the following recommendations.

- Change the raw material (M5) and (M2) to alternative materials which have lower embodied energy in their raw material extraction.
- Change the suppliers of the raw material (M5), (M6), (M7) and (M8) to local manufacturers. This applies more so for the raw material (M5) which came from New South Wales. This raw material needed to be transported over a long distance requiring the use of road transportation.

Fuel consumption will be high due to the heavy nature of the material and the distance needed to be travelled.

- Improve the transportation system by avoiding the use of road transportation over a long distance.
- Change the transportation types by leaning more towards water and rail transportation.

5.5.2 Cradle-to-grave Results and Discussion

As in the cradle-to-grave analysis, the input data in Section 5.4 and the Life Cycle Assessment method were used to assess the embodied energy of the whole life cycle of a mould fibreglass powerboat hull and a aluminium powerboat hull as shown in Figure 5.8. This assessment produced the embodied energy results from three different environmental aspects. They are the primary energy consumption, the greenhouse gas emissions and the total environmental impacts. These results are expressed in a unit of MJ_{eq} per powerboat hull, CO_{2eq} per powerboat hull and points per powerboat hull respectively.

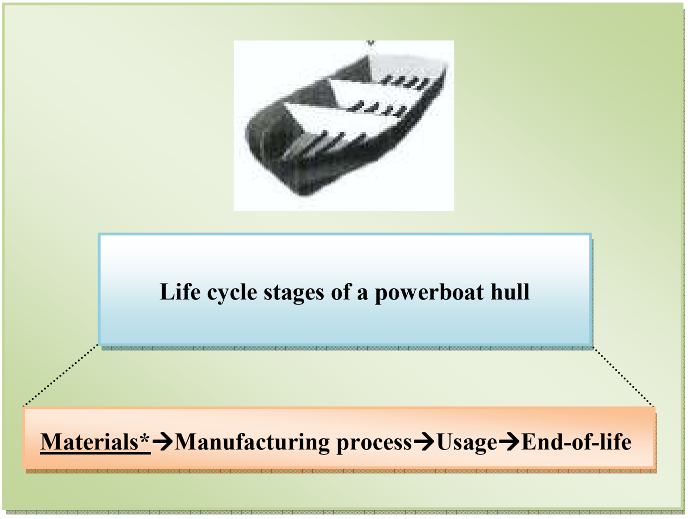


Figure 5.8: The life cycle stages of a powerboat hull.

In this section, the three results of the two powerboat hulls are presented in Figures 5.9 to 5.11. These charts display the results in terms of the life cycle stages which are the materials, manufacturing process, usage and end-of-life stages as illustrated in Figure 5.8. The last bar of the charts gives the total result of the two powerboat hulls which are the sum of the four life cycle stages. The blue bar presents aluminium powerboat hull and the green bar shows the mould fibreglass powerboat hull. In addition, a graph of the percentage difference between the embodied energy of the aluminium powerboat hull and the mould fibreglass powerboat hull are provided to facilitate the discussion in this section.

Figure 5.9 presents the embodied energy results from the perspective of the primary energy consumption which was assessed by the Cumulative Energy Demand version 1.04 (CED1.04) method as introduced in Section 5.2.2. The embodied energy of the powerboat hulls at the material life cycle stage are 782,224 MJ_{eq} per powerboat hull for the aluminium powerboat hull and 103,644 MJ_{eq} per powerboat hull for the mould fibreglass powerboat hull. This equates to a difference of 87% between the two materials. The reason for this is due to the fact that a relatively high amount of energy is required during the aluminium extraction process.

Another advantage of the moulded fibreglass powerboat hull is found at the manufacturing process stage in Figure 5.9 where the electricity consumption the manufacturing process is saved up to 39%. This is owing to the fact that the layers of the mould fibreglass powerboat hull is laid manually while the aluminium alloy (5086) uses the cold-forming and extrusion processes.

However, the shortcoming of the moulded fibreglass powerboat hull is in the end-of-life or the disposal life cycle stage where its embodied energy is significantly higher than the aluminium powerboat hull.

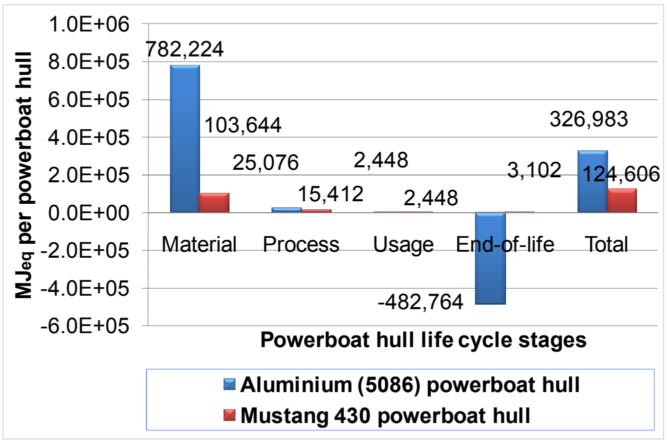


Figure 5.9: Comparison of the embodied energy results of the powerboat hulls in a unit of MJ_{eq}.

This was because an assumption was made that 65% of the aluminium could be recycled[43], whereas the moulded fibreglass hull was assumed as 100% landfill[44]. The assumptions were made based on the household waste data from Australian data 2007 library found in the Life Cycle Assessment software.

Therefore, the embodied energy of the aluminium powerboat hull at this stage is -482,764 MJ_{eq} per powerboat hull which indicates that the embodied energy was saved by 482,764 MJ_{eq} per powerboat hull from the recycling process of the aluminium hull. The mould fibreglass powerboat hull gains an embodied energy value of 3,102 MJ_{eq} per powerboat hull from the landfill process.

[43] The assumptions were made based on the household waste data from Australian data 2007 library of the Life Cycle Assessment software as shown in Appendix C.

[44] The assumptions were made based on the provided input data from Mustang Marine Australia Pty Ltd.

Overall, the total embodied energy results for the life cycle of the aluminium powerboat hull is 326,983 MJ_{eq} powerboat hull. The embodied energy of the mould fibreglass powerboat hull is 124,606 MJ_{eq} per powerboat hull. Figure 5.9 shows that the embodied energy for the life cycle of a powerboat hull can be reduced significantly by 62% when it is fabricated from the mould fibreglass instead of the aluminium. This dramatic reduction occurs at the material stage and is due to the embodied energy being 87% higher for the aluminium powerboat hull than that of the mould fibreglass powerboat hull.

Figure 5.10 presents the embodied energy results from the perspective of greenhouse gas emissions. These results were assessed by the IPCC GWP 100a version 1.00 (IPCC1.00) as presented in Section 5.2.2. The embodied energy of the powerboat hulls at the material life cycle stage are 67,577 kg CO_{2eq} per powerboat hull for the aluminium powerboat hull and 3,468 kg CO_{2eq} per powerboat hull for the mould fibreglass powerboat hull.

The difference between the two materials equates to a reduction in greenhouse gas emissions by 95%. This is due to the fact that a relatively high amount of energy is required during the aluminium extraction process. Therefore, the emissions of greenhouse gases are subsequently higher.

Another advantage of the mould fibreglass powerboat hull is found at the manufacturing process in Figure 5.10 where the electricity consumption is saved from the cold-transforming and extrusion processes by up to 38%.

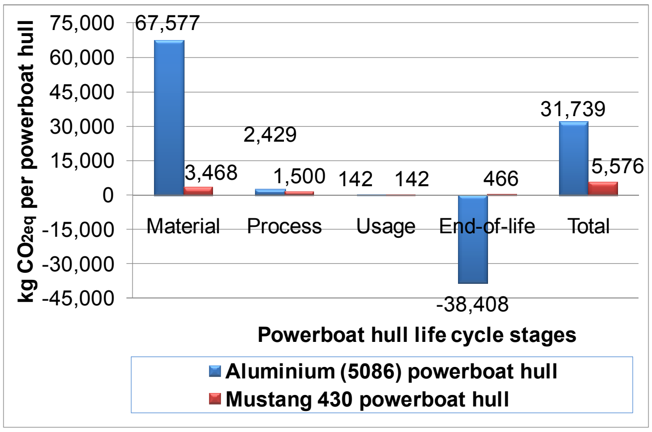


Figure 5.10: Comparison of the embodied energy results of the powerboat hulls in a unit of kg CO_{2eq}.

Nevertheless, the shortcoming of the mould fibreglass powerboat hull is in the end-of-life or the disposal life cycle stage of the aluminium powerboat hull performs significantly better than the mould fibreglass powerboat hull. This was because an assumption was made that 65% of the aluminium could be recycled, whereas the mould fibreglass powerboat hull was assumed as 100% landfill. These assumptions were made based on the household waste data from Australian data 2007 library of the Life Cycle Assessment software. Therefore, the aluminium power hull has the embodied of the end-of-life stage as

-38,408 kg CO_{2eq} per powerboat hull whereas the mould fibreglass powerboat hull gains an embodied energy value of 466 kg CO_{2eq} from the landfill process.

Overall, the total embodied energy results for the life cycle of the aluminium powerboat hull is 31,184 kg CO_{2eq} per powerboat hull whereby the embodied energy of the mould fibreglass powerboat hull is 5,576 kg CO_{2eq} per powerboat hull. Figure 5.10 shows that the embodied energy for the life cycle of a powerboat hull can be reduce by 82% when it is fabricated from the mould fibreglass instead of the aluminium. This dramatic reduction occurs at the material stage and is due to the embodied energy being 95% higher for the aluminium powerboat hull than that of the mould fibreglass powerboat hull.

Figure 5.11 presents the embodied energy results from the perspective of the total environmental impacts using the Eco-Indicator 99 H/A version 2.03 method as stated in Section 5.2.2. This is a comprehensive Life Cycle Assessment analysis as it calculates the environmental impacts that have an effect towards human health, the ecosystem quality and resource use. The calculation takes into account all emission substances such as airbourne and waterbourne emissions. These impacts are then calculated into a single score which is expressed in a unit of points.

The embodied energy of the powerboat hulls at the material life cycle stage are 3,033 points per powerboat hull for the aluminium powerboat hull and 549 points per powerboat hull for the mould fibreglass powerboat hull. This 82% reduction is due to the fact that a relatively high amount of energy is required during the aluminium extraction process.

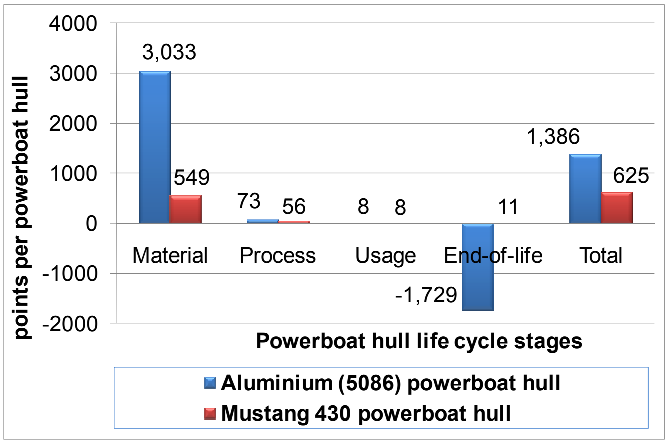


Figure 5.11: Comparison of the embodied energy results of the powerboat hulls in a unit of points per hull

Therefore, large amount of emission substances are emitted, which subsequently cause high environmental impacts.

Another advantage of the mould fibreglass powerboat hull is found at the manufacturing process stage in Figure 5.11 where the electricity consumption is saved from manual moulding process by up to 23%. Nevertheless, the shortcoming of the mould fibreglass powerboat hull is found in the end-of-life or the disposal life cycle stage of the aluminium powerboat hull performs better than the mould fibreglass powerboat hull. This was because an assumption was made that 65% of the aluminium could be recycled, whereas the mould fibreglass powerboat hull was assumed as 100% landfill. These assumptions were made based on the household waste data from Australian data 2007 library of the Life Cycle Assessment software. Therefore, the aluminium power hull saves the embodied of the end-of-life stage as -1,729 kg CO_{2eq} per powerboat hull whereas the mould fibreglass powerboat hull gains an embodied energy value of 11 kg CO_{2eq} from the landfill process.

Overall, the total embodied energy results for the life cycle of the aluminium powerboat hull is 1,386 points per powerboat hull, compared to the embodied energy of the mould fibreglass powerboat hull which is 625 points per powerboat hull. Figure 5.11 shows that the embodied energy for the life cycle of a powerboat hull can be reduced by 55% when it is fabricated from the mould fibreglass instead of the aluminium. This substantial reduction occurs at the material stage and is due to the embodied energy being 82% higher for the aluminium powerboat hull than that of the mould fibreglass powerboat hull.

According to the results presented in Figures 5.9 to 5.11, a powerboat hull manufactured from mould fibreglass has a significantly lower embodied energy value than a aluminium powerboat hull of the same dimension. The gained benefits in making a powerboat hull out of mould fibreglass rather than aluminium are described in the following three points.

- In terms of the energy consumption, a powerboat hull that is made from mould fibreglass can reduce its energy consumption during its life cycle by up to 62%.
- A powerboat hull that is made from mould fibreglass can reduce the amount of greenhouse gases emitted into the atmosphere by 82% during its life cycle.
- A powerboat hull that is made from mould fibreglass can reduce the total environmental impacts that can effect human health, the ecosystem quality and resource use by 55% its life cycle.

On the whole, these benefits are mainly gained during the material and manufacturing process stages of the powerboat hull life cycle. This is because the mould fibreglass uses significantly less extraction energy and electricity than one made from aluminium for the extraction as well as the hand lamination. However, the mould fibreglass powerboat hull has a slightly higher embodied energy than aluminium at the end-of-life stage due to the different disposal options.

5.6 Conclusion

This chapter presented the cradle-to-factory and the cradle-to-grave analyses which assessed the embodied energy for the raw materials of the mould fibreglass and the powerboat hulls that are made from the mould fibreglass and aluminium.

The methodology overview was presented by defining the scopes and assumptions of the input data which was required for the calculation of the embodied energy analysis. The Life Cycle Assessment method was selected to calculate the embodied energy of the raw materials and the two different powerboat hulls. This assessment produced the two embodied energy results and the full Life Cycle Assessment result. They were the primary energy consumption, the greenhouse gas emissions and the total environmental impacts.

These results were expressed in a unit of MJ_{eq}, kg CO_{2eq} and points respectively. The MJ_{eq} and kg CO_{2eq} results were the generic embodied energy values, however these two units only consider the primary energy consumptions and the greenhouse gas emissions. Therefore, the points results were generated from the full Life Cycle Assessment which covers all emission substances that can affect the environment in terms of human health, ecosystem and resource (fossil fuels and mineral) use.

Thereafter, the description of the raw materials and the two different powerboat hulls was specified. Consequently, the input data of the cradle-to-factory and the cradle-to-grave analyses was determined on the basis of the scopes, assumptions and descriptions.

The embodied energy results of the cradle-to-factory analysis demonstrated that the raw materials of a kilogram of mould fibreglass gave the embodied energy of 28 MJ_{eq}, 0.84 kg CO_{2eq} and 0.14 points. These results indicate that the primary energy sources such as crude oil and natural gas were consumed by 28 MJ_{eq}, the greenhouse gases were emitted by 0.84 kg CO_{2eq} and the total environmental impact was caused by 0.14 points during the raw material extraction and the associated transportation from suppliers to factory of a kilogram of mould fibreglass.

Insight of the contribution between the raw material extraction and the transportation involved, these results consist of 81% to 94% from the raw material extraction and 6% to 19% the transportation of the raw materials. The suggestions for reducing the embodied energy of the mould fibreglass were given in two different directions. They were using low embodied energy raw materials and choosing the suppliers that use a delivery transportation method that has a low embodied energy.

Subsequently, a hot spots analysis was performed to identify the raw materials or the suppliers that have significantly high embodied energy. Whilst, the embodied energy of the raw materials (M5), (M6) and (M2) are significantly higher than other raw materials, the transportation of the raw materials (M5), (M6), (M7) and (M8) are also substantially high. Some recommendations were given such as change to local manufacturers and avoiding as practically as possible the use of road transportation by leaning towards water and rail transportation.

The embodied energy results for the whole life cycle of a mould fibreglass powerboat hull and a aluminium powerboat hull were assessed using the cradle-to-grave analysis. These results illustrated that the embodied energy of the mould fibreglass powerboat hull is considerably lower than the aluminium powerboat hull. This is owing to the significant reduction in energy needed to extract the raw material during the material stage. Moreover, the mould fibreglass powerboat hull is very tough and highly corrosive resistance; henceforth it requires less maintenance activities than the aluminium powerboat hull.

In this analysis, the fuel consumption for performing the resurfacing process every 10 years was assumed for the aluminium powerboat hull whilst the mould fibreglass powerboat hull requires no resurfacing process during 30 years life span[45]. These advantages largely outweigh the disadvantages of utilising mould fibreglass which came from a slightly higher embodied energy value during the manufacturing process stage and the end-of-life stage.

The total embodied energy results of the two mould fibreglass powerboat hull life cycles revealed that:

- A powerboat hull that is made from the mould fibreglass consumes 62% less energy during its life cycle.
- A powerboat hull that is made from the mould fibreglass emits 82% less greenhouse gases during its life cycle compared to an aluminium powerboat hull.
- A powerboat hull that is made from the mould fibreglass has an environmental impact which is 55% less than that of an aluminium powerboat hull. This equates to a lessening on the effects towards human health, the ecosystem quality and resource use during its life cycle.

[45] www.mustangmarine.com.au

CHAPTER 6

EXEL COMPOSITES – EMBODIED ENERGY OF I-BEAM

6.1 Introduction

I-Beams are widely used as structural profiles in many building, construction and infrastructure applications as illustrated in Figure 6.1. Traditionally, I-Beams are made of conventional metals such as stainless steel and aluminium which are commonly fabricated by cold-transforming process. This is due to the fact that they have the required mechanical and physical properties such as the flexural stiffness, flexural modulus and corrosive resistance.

Alternatively, Exel Composites manufactures I-Beams that are made of a composite material which is a pultruded fibre composite. The material has similar properties to that of an I-Beam made from stainless steel. However, it differs in that it is lighter and has a lower material cost. The pultrusion process as presented in Figure 6.2 is used to fabricate the pultruded fibre composite. This process comprises of four main steps, namely reinforcement, pultrusion die, pulling unit and sawing unit.

Figure 6.1: Example of Exel structural profiles[46]

[46] www.exelcomposites.com

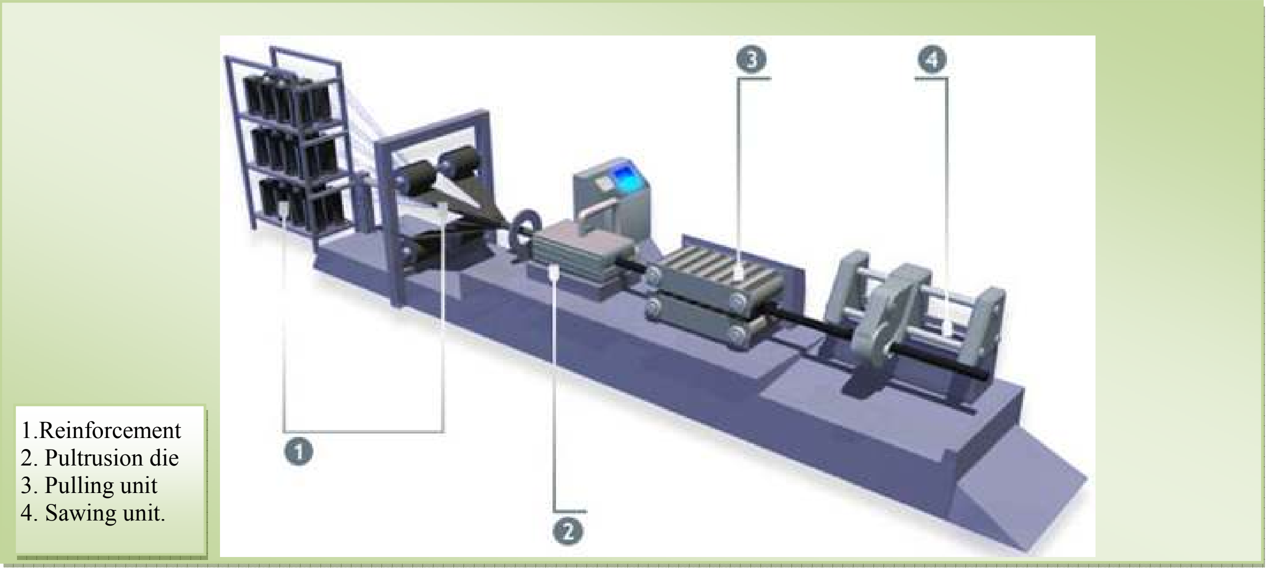


Figure 6.2: Pultrusion process[44].

Generally, the material selection for an I-Beam depends on the structural integrity, the capital investment and environmental requirement of the application. The pultruded fibre composite does have some physical and economical advantages over the traditional materials. However, in terms of their environmental performance, it is not so clear and therefore this project aimed to quantify the embodied energy of a linear metre of Exel I-Beam.

Therefore, this chapter aims to assess the embodied energy and the environmental impact of the raw materials that are used to make a kilogram of pultruded fibre composite manufactured by Exel Composites. Moreover, the embodied energy analysis is used to compare an I-Beam made from two different materials measuring 1 linear metre, namely pultruded fibre composite and the cold-formed stainless steel (316). Life Cycle Assessment is used as a tool to calculate the embodied energy of a kilogram of pultruded fibre composite and the two different I-Beams.

Cradle-to-factory[47] analysis is used in this chapter to determine the embodied energy and the total environmental impacts of the raw materials required to make a kilogram of the pultruded fibre composite. This material is used by Exel Composites to produce an I-Beam. In addition, cradle-to-grave analysis is employed to compare the embodied energy and the total environmental impacts of the life cycle of 1 linear

---

[47] Technically, the cradle-to-factory (gate) analysis is commonly defined as “an assessment of a partial product life cycle from manufacture ('cradle') to the factory gate before it is transported to the consumer” (Reference: Moreno, A., 2008, The DEPUIS HANDBOOK Chapter 4: Methodology of Life Cycle Assessment, Accessed: October 2009, http://www.depuis.enea.it/dvd/website.html). However, cradle-to-factory analysis in this project is specified as the embodied energy incurred during the raw material extraction and the transportation from suppliers to manufacturers.

metre I-Beams, which are made from pultruded fibre composite and cold-formed stainless steel (316). Theoretically, cradle-to-grave analysis is an assessment of a product life cycle including raw material extraction, manufacturing process, usage, transportation and end-of-life.

The outline of this chapter is as follows:

- Methodology overview of the cradle-to-factory and the cradle-to-grave analyses
- General scopes and assumptions of the analyses
- Description of a kilogram of pultruded fibre composite
- Description of a linear metre of an I-Beam that is made from pultruded fibre composite and cold-formed stainless steel (316)
- Input data of the cradle-to-factory and the cradle-to-grave analyses
- Cradle-to-factory results and discussion: the embodied energy of the raw materials require to make a kilogram of pultruded fibre composite
- Cradle-to-grave results and discussion: the comparison between a linear metre of I-Beams that is made from pultruded fibre composite and cold-formed stainless steel (316).
- Conclusion is drawn in the last section of the chapter

6.2 Methodology Overview

6.2.1 Embodied energy analysis

In this study, the embodied energy analysis of an I-Beam comprises of the cradle-to-factory and the cradle-to-grave analyses as shown in Figure 6.3. These analyses employ the Life Cycle Assessment method to assess the environmental impacts of all life cycle stages as shown in Figure 6.3. The methodology of these two analyses is described briefly as follows.

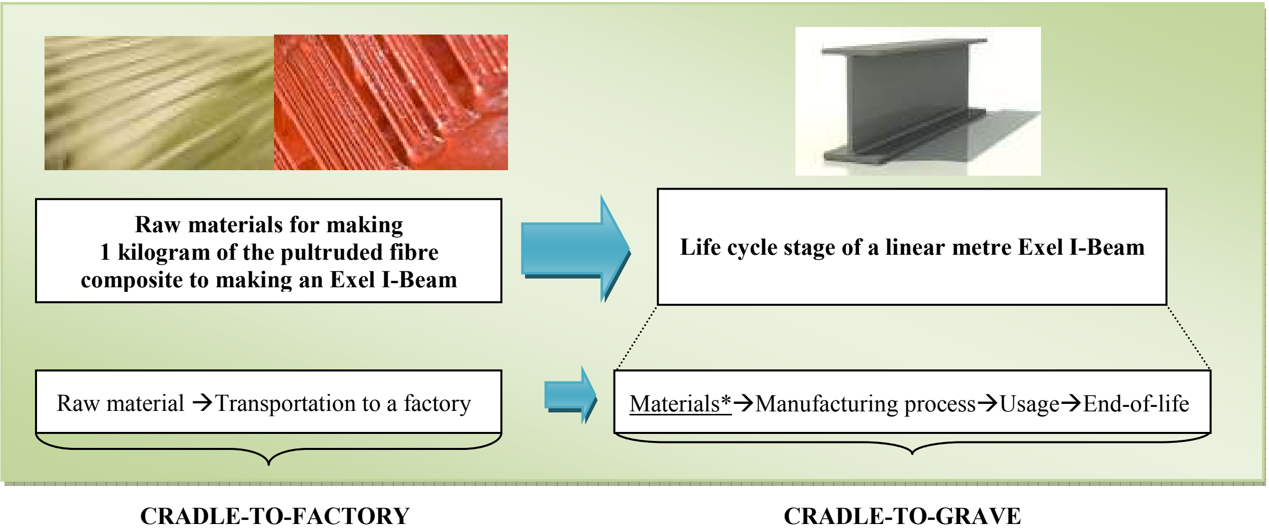


Figure 6.3: Scopes of cradle-to-factory and the cradle-to-grave analyses.

The methodology of these two analyses is described briefly as follows. Firstly, the cradle-to-factory analysis assesses the embodied energy in making 1 kilogram of the pultruded fibre composite as presented in the left portion of Figure 6.3. This analysis focuses on two main embodied energy sources. They are the raw material extraction and the transportation of raw materials from the supplier to a factory, i.e. Exel Composites. The asterisk sign next to the word 'Materials' in Figure 6.3 indicates that the embodied energy result from this analysis will be used as the input data for the materials stage in the next analysis.

Secondly, the cradle-to-grave analysis as shown in Figure 6.3 calculates the life cycle of a 1 linear metre of Exel I-Beam. For comparison purposes this analysis technique is also performed on a stainless steel (316) I-Beam of a dimension with equivalent flexural stiffness to Exel I-Beam. The life cycle stages of these products are presented on the right hand side of Figure 6.3 where:

- The materials stage is the total raw materials that are used in making the two I-Beams;
- The manufacturing process stage comprises the processes involved in making the I-Beam;
- The usage stage consists of the activities that occur after the I-Beams are manufactured i.e. the installation and maintenance activities, until the product is disposed of;
- The end-of-life stage is the disposal scenario which includes the transportation of the I-Beams to the disposal site and the disposal process.

Finally, the embodied energy results from the cradle-to-factory analysis are discussed and the hot spots identified. For this project a hot spot is defined as the raw materials and/or suppliers which have a high contribution to the embodied energy results. The hot spots analysis was conducted in order to make further suggestions in order to minimise or eliminate the identified raw materials and/or suppliers.

Subsequently, the embodied energy results from the cradle-to-grave analysis of Exel I-Beam are analysed and compared with the life cycle of the cold-formed stainless steel (316) I-Beam.

6.2.2 Scopes and assumptions of the embodied energy analysis

This section presents Tables 6.1 and 6.2 to clarify the scopes and assumptions that were made for the cradle-to factory and the cradle-to-grave analyses. Table 6.1 provides the main scope of the cradle-to-factory analysis which focuses in quantifying the embodied energy of the raw materials in making a kilogram of the pultruded fibre composite. Subsequently, the scopes of the input data that are associated with the raw material extraction and their transportation are given in Table 6.1. Furthermore, Table 6.1 shows the data sources that are used to make the assumptions for the input data of the cradle-to-factory analysis. Overall, the input data in terms of the quantities and the types of materials and transportation were provided by Exel Composites. The rest of the data was obtained by using further literature reviews and the libraries from the database of the LCA software, SimaPro 7.1.8.

<table>
<tr><th colspan="9">CRADLE-TO-FACTORY</th></tr>
<tr><td colspan="9">Scope: To quantify the embodied energy of the raw materials in making 1 kilogram of the pultruded fibre composite.</td></tr>
<tr><td>Input data</td><td colspan="8">Amount of the raw materials used in making 1 kilogram of the pultruded fibre composite.</td></tr>
<tr><td rowspan="2">Material life cycle stage</td><td rowspan="2">Scopes and assumptions</td><td colspan="7">Data sources</td></tr>
<tr><td>EX</td><td>LR</td><td>AU</td><td>BU</td><td>ET</td><td>FR</td><td>ID</td></tr>
<tr><td rowspan="2">Raw material extraction</td><td>Amount of raw materials (kg)</td><td>✓</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Material types</td><td>✓(MSDs)</td><td></td><td>✓</td><td></td><td>✓</td><td></td><td>✓</td></tr>
<tr><td rowspan="3">Transportation of raw materials:
From: Suppliers
To: Exel Composites (Queensland)</td><td>The locations of suppliers</td><td>✓</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Distance (km): Measure by using the online maps</td><td></td><td>✓</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Transportation types</td><td>✓</td><td></td><td>✓</td><td>✓</td><td></td><td>✓</td><td></td></tr>
</table>

Note: Exel Composites (EX), Literature review (LR), the 'Australia data 2007'(AU), the 'BUWAL 250' (BU), the 'ETH-ESU 96' (ET), the 'Franklin USA 98'(FR) and the 'IDEMAT2001'(ID) libraries are the databases from the SimaPro 7.1.8 software.

Table 6.1: Scopes and assumptions of cradle-to-factory analysis.

For instance, the input data for the amount of raw material was based on the information from the Material Safety Datasheets (MSDs) which were provided by Exel Composites. The material types were assumed using the Australian Data 2007 (AU) library and the distance of the transportation of raw materials was found using the online maps provided by Google. Similarly, Table 6.2 presents the scopes of the cradle-to-grave analysis for the life cycle of the two I-Beams. The life cycle input data in terms of the quantities and types are assumed based on the data sources as shown in the table.

CRADLE-TO-GRAVE

Scope: To analyse the embodied energy for the life cycle of the 1 linear metre I-Beams that made from the pultruded fibre composite and the cold-formed stainless steel (316).

Life cycle stages of the I-Beams	Scopes and assumptions	Data sources							
		EX	LR	AU	BU	DA	ET	FR	ID
Material stage: *Input data* Raw material extraction	Amount of the raw materials per 1 linear meter I-Beam *Exel I-Beam:*								
	Weight: 3.28 kg per linear meter	✓							
	Material type: Multiply the raw material extraction results from the cradle-to-factory analysis which is produced in the unit of per kg with 3.28 kg per linear meter	✓		✓			✓		✓
	Cold-formed stainless steel (316) I-Beam: **Weight:** 3.93 kg per linear meter	✓							
	Material type: Stainless steel with DIN 1.4401, AISI 316 is assumed.	✓							✓
Material stage: *Input data* Transportation of raw materials: *From:* A Supplier *To:* Exel Composites	*Exel I-Beam:* Multiply the transportation of raw materials results from the cradle-to-factory analysis which is produced in the unit of per kg with 3.28 kg/ linear meter	✓		✓	✓			✓	
	Cold-formed stainless steel (316) I-Beam: **Distance*:** - From Wollongong. Use the online map to measure the distance (km)		✓						
	By*: Articulated truck for freight	✓		✓		✓			✓
Manufacturing process: *Input data*	*Exel I-Beam:* **Amount:** Total Electricity consumption	✓							
	Energy type: Electricity in Victoria			✓					
	Cold-formed stainless steel (316) I-Beam: It is assumed to be cold-transformed.		✓	✓		✓			✓
Usage: *Input data* Installation *From:* Exel Composites *To:* A customer	*Both I-Beams:* **Distance***: 200 km is assumed **By***: Articulated truck for freight			✓					
Usage: *Input data* Maintenance	*Both I-Beams:* Same activities, it is excluded.	✓							
End-of-life: *Input data* Disposal transportation *From:* A customer *To:* A disposal site	*Both I-Beams:* **Distance***: 200 km **By***: Articulated truck for freight			✓					
End-of-life: *Input data* Disposal scenarios	*Exel I-Beam:* **Household waste**: 100% landfill	✓		✓					
	Cold-formed stainless steel (316) I-Beam: **Household waste**: 70% recycling	✓		✓					

*Note: *Arbitrary assumption is used a standard value for the 'Composites: Calculating their Embodied Energy Study' where 200 km was suggested by one of the participant composite company.*

Exel Composites (EX), Literature review (LR),the 'Australia data 2007'(AU), the 'BUWAL 250' (BU), the 'Data archive' (DA), the 'ETH-ESU 96' (ET), the 'Franklin USA 98'(FR) and the 'IDEMAT2001'(ID) libraries are the databases from the SimaPro 7.1.8 software.

Table 6.2: Scopes and assumptions of cradle-to-grave analysis for the pultruded fibre composite.

It is worth highlighting the assumption for the material stage of the Exel I-Beam which has the embodied energy from the raw material extraction and the transportation of those materials. In this stage, the embodied energy of Exel I-Beam is assumed to be calculated directly from the embodied energy results of the cradle-to-factory analysis. The calculation is carried out by multiplying the raw material extraction results from the cradle-to-factory analysis which is produced in the unit of per kg with 3.28 kg/linear metre. Whereby, the transportation of raw materials results from the cradle-to-factory analysis is also multiplied by 3.28 kg/linear metre. For instance, the embodied energy result of the raw material extraction from the cradle-to-factory analysis is 23 MJ_{eq} per kg and the weight of Exel I-Beam is 3.281 kg/linear metre. Therefore, the embodied energy result for the raw material extraction during the material stage in the cradle-to-grave analysis is:

$$23\ MJ_{eq} \text{ per kg} \times 3.281 \text{ kg.per linear metre} = 75.46\ MJ_{eq} \text{ per linear metre}$$

In addition, certain input data for the life cycle of the two I-Beams was assumed arbitrarily. For example, to install an I-Beam, the transportation distance from Exel Composites to a customer during the usage stage was assumed to be 200 kilometres. The articulated truck was also assumed as the transportation method to dispose of an I-Beam at its end-of-life stage.

Table 6.3 is given to clarify scopes and the assumptions of the embodied energy calculation tool which was selected for the cradle-to-factory and cradle-to-grave analyses. As a result, three Life Cycle Impact Assessment methods from the SimaPro 7.1.8 software were selected as shown in the table. They are the Cumulative energy demand version 1.04 (CED1.04), the IPCC GWP 100a version 1.00 (IPCC1.00) and the Eco-Indicator 99 H/A version 2.03 (EI992.03) methods. Furthermore, Table 6.3 also summarises the calculation approach and the results of the three methods for the cradle-to-factory and cradle-to-grave analyses. These methods generated the embodied energy results for these analyses in the units of MJ_{eq}, kg CO_{2eq} and points per kg as well as in units of MJ_{eq}, kg CO_{2eq} and points per linear metre. Therefore, Figure 6.4 is given to provide additional information to aid in how to interpret these results. Additionally, the amount of six conventional air pollutants as listed in Table 6.3 are as the total airbourne substances that are emitted during the cradle-to-factory and cradle-to-grave analyses.

<table>
<tr><th colspan="5">EMBODIED ENERGY CALCULATION TOOL</th></tr>
<tr><th>Embodied Energy Analysis</th><th colspan="4">Scopes and Assumptions</th></tr>
<tr><td>Embodied energy assessment tool</td><td colspan="4">The Life Cycle Impact Assessment methods from the LCA software, SimaPro 7.1.8 software.</td></tr>
<tr><td>Selection of the Life Cycle Impact Assessment methods</td><td colspan="4">The selection of these methods was based on the generic embodied energy analysis which is often based on the input-output model that is used to quantify the primary energy sources and often expressed in MJ and in kg of CO_2 units. In addition, as the two values from the Cumulative energy demand version 1.04 and the IPCC GWP 100a version 1.00 methods only represent the embodied energy in terms of the primary energy consumption and the impacts from the climate change respectively. Therefore, the points value is also given. This value is calculated from Life Cycle Assessment which considers the impacts on human health, the ecosystem quality and resource use. The points value is calculated from the Eco-Indicator 99 H/A version 2.03 method.</td></tr>
<tr><th colspan="5">LIFE CYCLE IMPACT ASSESSMENT METHODS</th></tr>
<tr><th rowspan="2">Method</th><th rowspan="2">Calculation Approach and unit</th><th colspan="3">Embodied Energy Results</th></tr>
<tr><th>Cradle-to-factory</th><th>Cradle-to-grave</th><th>Amount of conventional air pollutions</th></tr>
<tr><td>Cumulative energy demand version 1.04 (CED1.04)</td><td>Calculation: Calculates the embodied energy in terms of the consumption of the primary energy sources such as fossil fuels, minerals, renewable energy.
Unit: MJ_{eq}</td><td>MJ_{eq} per kg</td><td>MJ_{eq} per linear metre</td><td rowspan="3">Carbon monoxide (CO)
Carbon dioxide (CO_2)
Nitrogen dioxide (NO_2)
Sulphur dioxide (SO_2)
Unspecified particulate
Volatile organic compounds (VOC)</td></tr>
<tr><td>IPCC GWP 100a version 1.00 (IPCC1.00)</td><td>Calculation: Calculates the greenhouse gas emissions which impact the global warming.
Unit: kg CO_{2eq}</td><td>kg CO_{2eq} per kg</td><td>kg CO_{2eq} per linear metre</td></tr>
<tr><td>Eco-Indicator 99 H/A version 2.03 (EI992.03)</td><td>Calculation: calculates as the environmental performance indicator as a single score. This is a comprehensive Life Cycle Assessment analysis which considers human health, the ecosystem quality and resource use impacts.
Unit: points of a single score</td><td>points per kg</td><td>points per linear metre</td></tr>
</table>

Table 6.3: Scopes and assumptions for the embodied energy calculation tools and results.

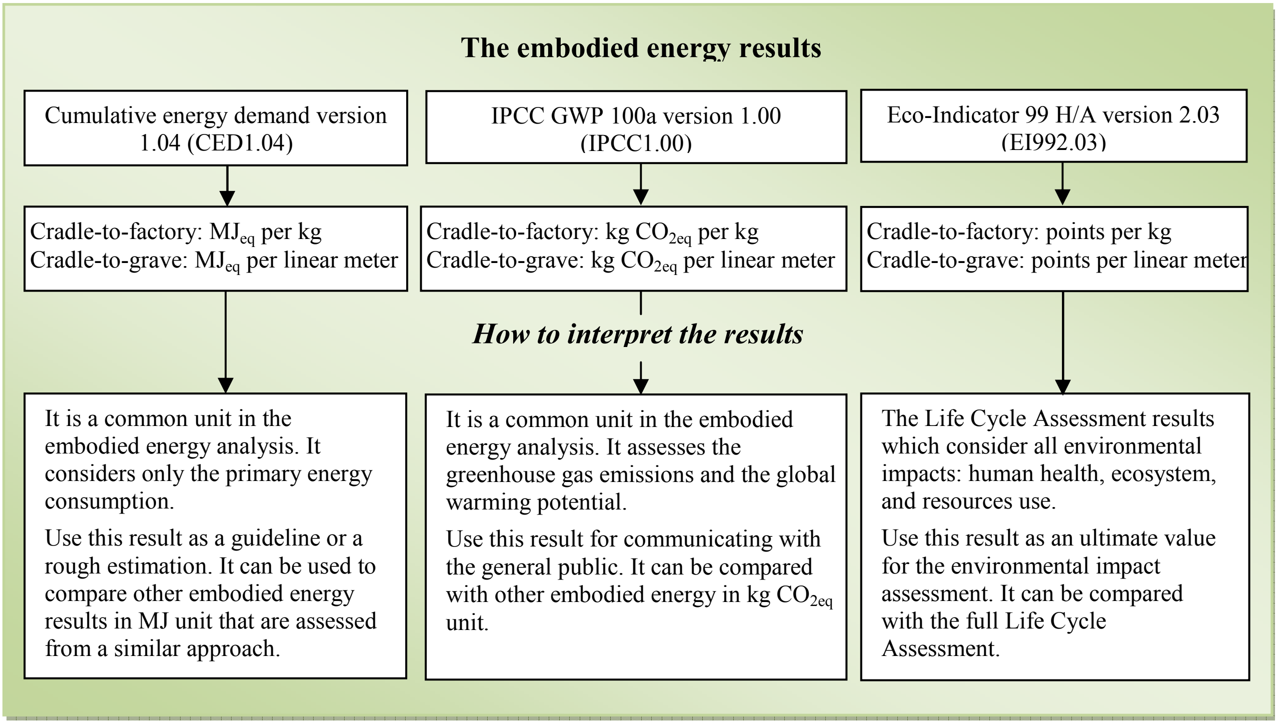


Figure 6.4: How to interpret the embodied energy results.

6.3 Material and Product description

6.3.1 Pultruded fibre composite description

The description of the raw materials used in manufacturing of the pultruded fibre composites manufactured by Exel Composites is summarised in Table 6.4. Various raw materials constitute the composite material such as fibreglass, plastic resins as well as pigment, catalysts, gel-coat and additives. These raw materials are supplied by 14 suppliers from Australia, Asia and US regions. The transportation of the raw materials from suppliers to Exel Composites located in Victoria involves road and water transportation. The transportation of the raw materials is presented in the last column of Table 6.4. Some of the raw materials transported from the supplier to Exel Composites require only one transportation method while others need several.

Raw material type	List of raw material	Region of supplier	Road and water transportation of raw material: from a supplier to the factory, Exel Composites (Exel.)
Fibre glass	M8 and M9	Asia and US	Supplier *(M8and M9) → (M_T1) → (M_T2) → (M_T3) → Factory (Exel.)
Resin	M3, M4 and M5	Australia and US	Supplier *(M3and M5) → (M_T1) → Factory (Exel.) and Supplier *(M4) → (M4_T1) → (M4 _T2) → (M4_T3) → Factory (Exel.)
Others: such as pigment, catalysts, gel-coat and additives	M1, M2, M6, M7and M10 to M14	Asia, Australia and US	Supplier *(M2, M6 and M13) → (M_T1) → Factory, (Exel.) Supplier *(M1, M10 to M12) → (M_T1) → (M_T2) → Factory, (Exel.) Supplier *(M7) → (M7_T1) → (M7 _T2) → (M7_T3) → Factory (Exel.) and Supplier *(M14) → (M14_T1) → (M14_T1) → (M14_T1) → (M14_T1) → Factory: (Exel.)

Note: The abbreviations of 'M' and "M_T' are provided for the discussion of Figure 6.8.
Raw material types (M), First transportation of the raw material (M_T1), Second transportation of the raw material (M_T2), Third transportation of the raw material (M_T3), Fourth transportation of the raw material (M_T4),

(Road transportation such as a truck) and (Water transportation such as an Australian international shipping)

Table 6.4: Raw materials and the transportation of raw materials in making a kilogram of the pultruded fibre composite

Additionally, Table 6.4 presents the abbreviations of the raw material type 'M' and its transportation 'M_T' which are provided for later discussion in this chapter. As there are 14 suppliers involved in this analysis, M1 to M14 and also M1_T1 to M14_T4 present in Table 6.4.

6.3.2 A linear metre I-Beam description

The cradle-to-grave analysis focuses on assessing the embodied energy of an I-Beam measuring 1 linear metre. The dimension and weight of the 1 linear metre I-Beams are:

- Exel I-Beam (150x76x6mm) = 3.28 kg per linear metre
- Cold-formed Stainless Steel I-Beam (76.67x38.1x3.41mm) = 3.93 kg per linear metre

The stainless steel I-Beam dimension was calculated by Exel Composites as shown in Figure 6.5. Figure 6.6 presents the drawing of the I-Beams with the dimensions.

Competitive Material: Stainless Steel I-beam

Consider the mechanical properties of 316 stainless steel with respect to FRP:

	Tensile Modulus [MPa]	Tensile Strength [MPa]	Flexural Modulus [MPa]	Flexural Strength [MPa]	Density [g/cm³] (SG)
Stainless Steel (316)	193,000	515	193,000	552	7.9
FRP (Mat & Roving) (longitudinal direction)	17,200	207	13,800	207	1.72

The most dominant mechanical property for an I-beam is its flexural modulus. It is evident that 316 stainless steel has a flexural modulus that is much higher, which translates to a smaller size I-beam compared to the pultruded FRP.
To calculate a beam of equivalent flexural stiffness, the flexural modulus, Ef, multiplied by the moment of inertia, I, will be compared and the moment of inertia of the stainless steel beam will be calculated by the following equation:

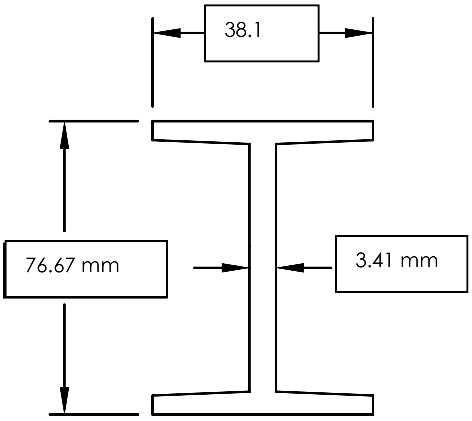
$$Ef_{ss} I_{ss} = Ef_{FRP} I_{FRP}$$

Where:

- Ef_{ss} = 193,000 MPa
- Ef_{FRP} = 13,800 MPa
- I_{FRP} = 6,234,800 mm^4

Solving for I_{ss} = 445,461 mm^4

The pultruded FRP beam is to be compared with the embodied energy for a 316 stainless steel beam that has the following dimensions that translate to the same flexural stiffness (EI):



Cross-sectional area of I-beam = 498.03 mm^2

Figure 6.5: Dimension calculation for cold-formed stainless steel (316) I-Beam[48].

[48] www.exelcomposites.com

(a) Exel I-Beam (b) Cod-formed stainless steel (316) I-Beam

Figure 6.6: The dimensions of the two different I-Beams (*All dimensions are in millimetres*)

6.4 Input Data

The input data of the cradle-to-grave analysis for the two I-Beams made from the pultruded fibre composite and the cold-formed stainless steel (316) are presented in Tables 6.5 and 6.6 respectively. This input data was derived from the scopes and the assumptions in Section 6.2.2. Therefore, the input data of all life cycle stages are presented in terms of a unit, the amount and the 'material/process description' which represents the material and the manufacturing process types.[49]

Life Cycle stage	Material/process description	Unit	Amount	Data source
Material: Pultrusion fibre composite	Pultrusion fibre composite	kg	3.281	Multiply 1 kg results from the cradle-to-factory analysis by 3.281
Manufacturing process: Pultrusion process	High voltage electricity in Victoria for the pultrusion process	kWh	1.1014	Australian Data 2007 LCI library
Usage: Installation transportation	Articulated truck freight, customisable/AU U: 3.281E-03tonne×200km	tkm	0.6562	Australian Data 2007 LCI library
End-of-life: Disposal transportation	Articulated truck freight, customisable/AU U: 3.281E-03tonne×200km	tkm	0.6562	Australian Data 2007 LCI library
End-of-life: 100% landfill process	Landfill	%	100	Australian Data 2007 LCI library

Table 6.5: Input data for a 1 linear metre Exel I-Beam.

[49] In relation to this, the data sources for the input data of 'Material/process description' and 'Amount' are also given in the last column of Tables 6.5 and 6.6for the reference of the database background.

Life Cycle stage	Material/process description	Unit	Amount	Data source
Material: Stainless steel (316)	Stainless steel (316)	kg	3.93	IDEMAT2001
Material: Transportation	Articulated truck freight from Wollongong to Queensland 3.93E-03tonne×815km	tkm	3.20295	Australian Data 2007 LCI library
Manufacturing process: Cold transforming process	Cold transforming process	kg	3.93	Australian Data 2007 LCI library
Usage: Installation transportation	Articulated truck freight, customisable/AU U: 3.93E-03tonne×200km	tkm	0.786	Australian Data 2007 LCI library
End-of-life: Disposal transportation	Articulated truck freight, customisable/AU U: 3.93E-03tonne×200km	tkm	0.786	Australian Data 2007 LCI library
End-of-life: 70% Recycling process	Household waste which recycling steel at 70% rate	%	100	Australian Data 2007 LCI library

Table 6.6: Input data for 1 linear metre of a stainless steel (316) I-Beam.

6.5 Embodied Energy Results

6.5.1 Cradle-to-factory Results and Discussion

The cradle-to-factory analysis was carried out by using the Life Cycle Assessment method to assess the embodied energy of the raw materials that are comprised in a kilogram of the pultruded fibre composite as presented in Figure 6.7. This assessment produced the two embodied energy results and the full Life Cycle Assessment result. They are the primary energy consumption, greenhouse gas emissions and the total environmental impacts or a single score. These results are expressed in a unit of MJ_{eq} per kg, kg CO_{2eq} per kg and points per kg respectively.

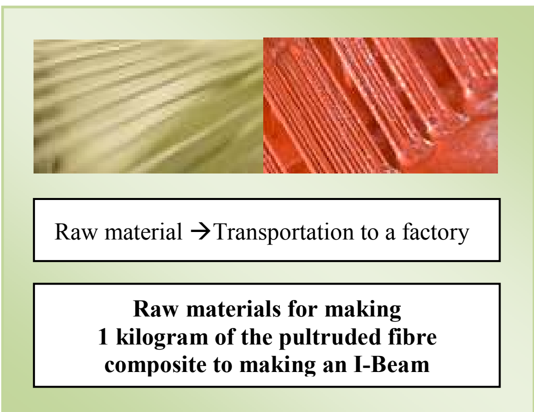
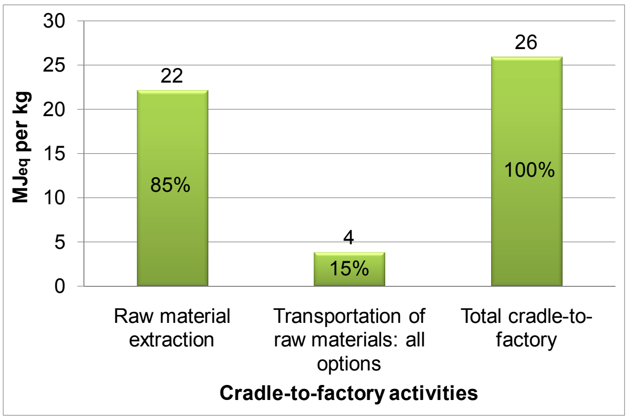
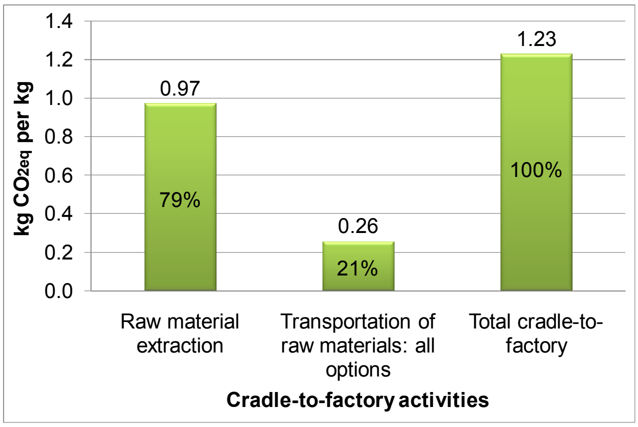


Figure 6.7: Two main embodied energy sources of cradle-to-factory analysis (the resin photo was taken from www.exelcomposites.com.

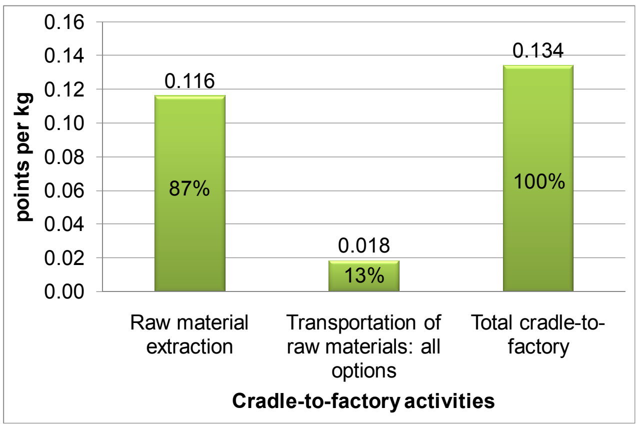
The total results of these two embodied energy sources are also provided in the last bar of Figures 6.8 (a) to (c). On the whole, the raw materials for a kilogram of pultruded fibre composite give a total embodied energy results of 26 MJ_{eq}, 1.23 kg CO_{2eq} and 0.13 points. These charts display the results in terms of the raw material extraction and the transportation of the raw materials from suppliers to Exel Composites as depicted in Table 6.4.



(a) Primary energy consumption results in MJ_{eq} per kg



(b) Greenhouse gas emission results in kg CO_{2eq} per kg



(c) Total environmental impacts results in points per kg

Figure 6.8: Cradle-to-factory results for the pultruded fibre composites of Exel Composites

The last bar of the charts gives the total results of the two main embodied energy sources which are the sum of the raw material extraction and the transportation of raw materials. These results consist of 79% to 87% from the raw material extraction and 13% to 21% from the transportation of the raw materials as labelled in Figure 6.8. The distinct contributions of the two embodied energy sources are clearly revealed. The finding suggests that the embodied energy of the pultruded fibre composite can be reduced in two different directions.

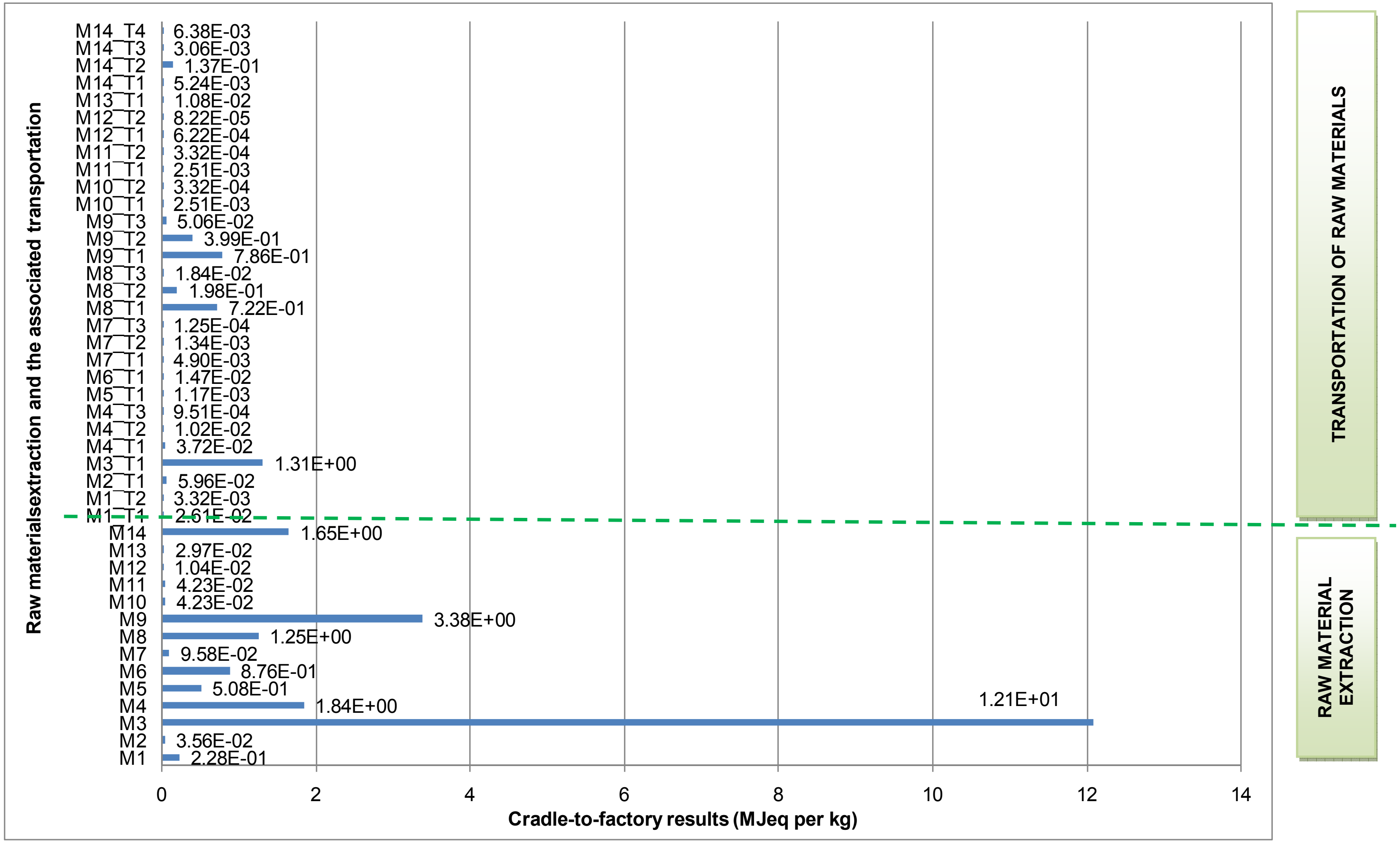
The first direction is to reduce the high embodied energy of the raw material extraction by using alternative raw materials with low embodied energy. The second direction is to be selective in choosing the suppliers in order to ensure low embodied energy in their delivery transportation.

Ideally, the first direction would be the best option as it can reduce the embodied energy dramatically by changing some of the raw materials as the raw material extraction actually contributes a large portion in the total embodied energy result. However, it requires further research and development in finding an alternative or a new raw material which requires further investment of the supporting systems. Therefore, this direction can only be targeted as a long term product development plan. In practice, the second direction would be more attractive as it is a fast and a simple approach which requires only a careful consideration in selecting the suppliers. For instance, the selected suppliers should supply the raw materials that are manufactured locally or require less energy-intensive transportation system for transporting the raw materials.

To enhance the implementation of these suggestions, Figure 6.8 explicitly presents the embodied energy for each raw material and its corresponding transportation method. These results are produced from the detailed input data such as the Material Safety Datasheets and the actual location of the suppliers for all raw materials provided by Exel Composites.

Figure 6.9 reveals that the embodied energy of the pultruded fibre composite from Exel Composites was dominated by the combination of several raw materials which originated from overseas suppliers. As a result, a number of hot spots which are the raw materials or the suppliers that have significantly high values are revealed in Figure 6.9.

In this occasion, the raw material (M3) contributes the most followed by the raw material (M9), (M4), (M14), (M8), (M6), (M5) and (M7) whereby the obvious hot spots of the supplier's transportation are the transportations of the raw materials (M3), (M9), (M8) and (M14). Similarly, these higher contributions of the embodied energy for the transportation methods were observed with notable reasons. Since these raw materials were required in high quantities, they needed to be imported from overseas. Therefore a combination of transportation types was utilised. At the same time, some of the locally-supplied raw materials also needed to be transported on road over a significantly long distance i.e. the transportation of raw material (M3) from Queensland to Victoria.



Note:Raw material types (M), First transportation of the raw material (M_T1), Second transportation of the raw material (M_T2), Third transportation of the raw material (M_T3), Fourth transportation of the raw material (M_T4),

Figure 6.9: Detailed embodied energy results (MJ_{eq}/kg) of the cradle-to-factory analysis which displays types and transportation of raw materials.

Consequently, these hot spots can be minimised and eliminated by approaching the following recommendations.

- Change the raw material (M3) and (M9) to alternative materials which have lower embodied energy in their raw material extraction.
- Alternatively, if those two materials are the core ingredients, change the raw material (M4), (M14), (M8), (M6), (M5) or (M7) to other materials which have lower embodied energy in their raw material extraction.
- Change the suppliers of the raw material (M3), (M8), (M9) and (M14) to local manufacturers. This is in particular for the raw material (M8) which came from the US region and also involved in the long distance travel by the road transportation.
- Improve the transportation system by avoiding to use the road transportation for a long distance.
- Change the transportation types by leaning towards the water and rail transportation

6.5.2 Cradle-to-grave results and discussion

As in the cradle-to-grave analysis, the Life Cycle Assessment method was used to assess the embodied energy of the whole life cycle of a linear metre Exel I-Beam and a linear metre cold-formed stainless steel (316) I-Beam as shown in Figure 6.10. This assessment produced the embodied energy results from three different environmental aspects. They are the primary energy consumption, the greenhouse gas emissions and the total environmental impacts. These results are expressed in a unit of MJ_{eq} per linear metre, CO_{2eq} per linear metre and points per linear metre respectively.

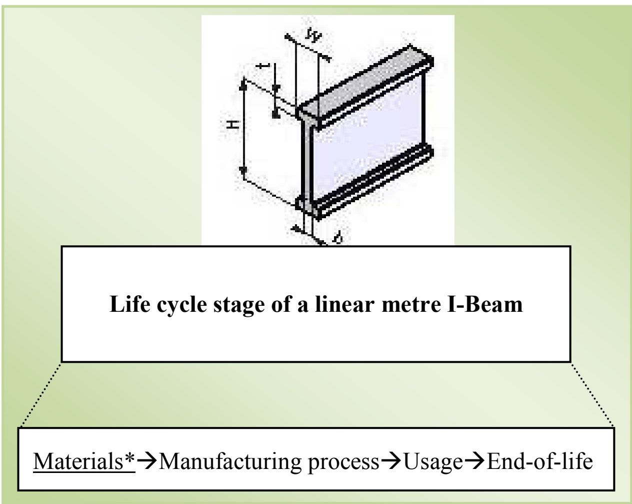


Figure 6.10: The life cycle stages of a linear metre I-Beam

In this section, the three results of the two I-Beams are presented in Figures 6.11 to 6.13. These charts display the results in terms of the life cycle stages which are the materials, manufacturing process, usage and end-of-life stages as illustrated in Figure 6.10. The last bar of the charts gives the total result of the two I-Beams which are the sum of the four life cycle stages. The blue bar presents the cold-formed stainless steel (316) I-Beam and the green bar shows Exel I-Beam.

Figure 6.11 presents the embodied energy results from the environmental aspect of the primary energy consumption which was assessed by the Cumulative Energy Demand version 1.04 (CED1.04) method as introduced in Section 6.2.2. The embodied energy of the I-Beams at the material life cycle stage are 240 MJ_{eq} per linear metre for the cold-formed stainless steel (316) I-Beam and 85 MJ_{eq} per linear metre for Exel I-Beam. This equates to a difference of 65% between the two materials. The reason for this is due to stainless steel consist of not only steel but also other metals such as chromium, manganese and nickel the fact. These metals require a relatively high amount of energy for their extraction process.

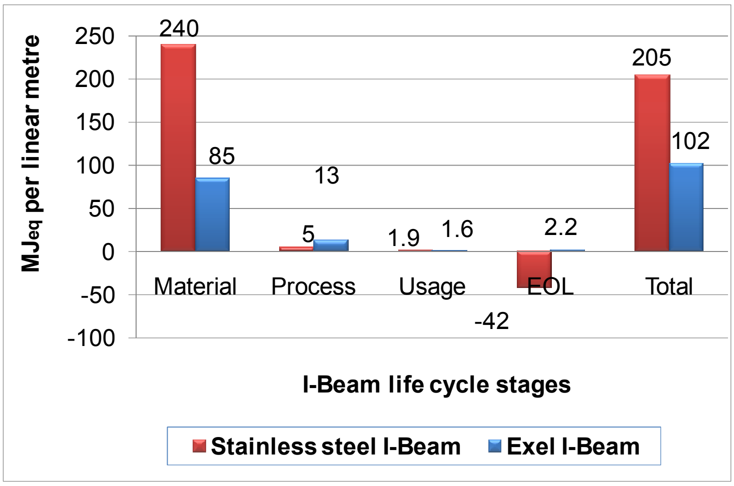


Figure 6.11: Comparison of the embodied energy of an I-Beam made from two different materials measuring 1 linear metre using the Cumulative Energy Demand method

Another advantage of the Exel I-Beam is found at the usage stage in Figure 6.11 where 16% of the fuel consumption is saved during the installation activities as this I-Beam is lighter than the cold-formed stainless steel (316) I-Beam. Nevertheless, the shortcoming of the Exel I-Beam is in the manufacturing process where its embodied energy is considerably higher than the cold-formed stainless steel (316) I-Beam by 62%.

However, the end-of-life or the disposal life cycle stage of the cold-formed stainless steel (316) I-Beam performs better than the pultruded fibre composite I-Beam. This was because an assumption was made that 70% of the stainless steel[1] could be recycled, whereas Exel I-Beam was assumed as 100%

[1] The assumptions were made based on the household waste data from Australian data 2007 library of the Life Cycle Assessment software as shown in Appendix C.

landfill[2]. Therefore, the embodied energy of the cold-formed stainless steel (316) I-Beam at this stage is -42 MJ_{eq}. This indicates that energy is gained back from the recycling process by 42MJ_{eq}. The Exel I-Beam gains an embodied energy value of 2 MJ_{eq} from the landfill process.

Overall, the total embodied energy results for the life cycle of the cold-formed stainless steel (316) I-Beam is 205 MJ_{eq} per linear metre. The embodied energy of the pultruded fibre composite is 102 MJ_{eq} per linear metre. Figure 6.11 shows that the embodied energy for the life cycle of a linear metre I-Beam can be reduced significantly by 50% when it is fabricated from the pultruded fibre composite instead of the cold-formed stainless steel (316). This dramatic reduction occurs at the material stage and is due to the embodied energy being 65% higher for the cold-formed stainless steel (316) I-Beam than that of the pultruded fibre composite.

Figure 6.12 presents the embodied energy results from the perspective of greenhouse gas emissions. These results were assessed by the IPCC GWP 100a version 1.00 (IPCC1.00) as presented in Section 6.2.2. The embodied energy of the I-Beams at the material life cycle stage are 20 kg CO_{2eq} per linear metre for the cold-formed stainless steel (316) I-Beam and 4 kg CO_{2eq} per linear metre for the pultruded fibre composite I-Beam. The difference between the two materials equates to a reduction in greenhouse gas emissions by 80%. This is due to the fact that a relatively high amount of energy is required during the extraction process of the metals used in making stainless steel (316) such as chromium, manganese and nickel. Therefore, the emissions of greenhouse gases are subsequently higher.

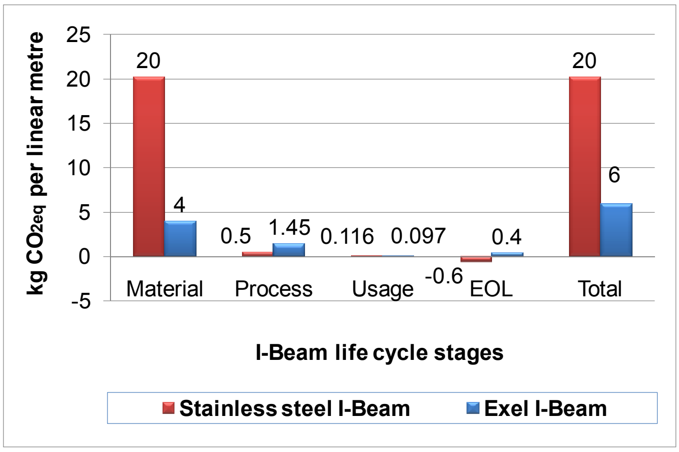


Figure 6.12: Comparison of the embodied energy of an I-Beam made from two different materials measuring 1 linear metre using the IPCC GWP 100a method

Another advantage of Exel I-Beam is found at the usage stage in Figure 6.12 where there is a reduction in greenhouse gas emissions of 16% during the installation activities. This is due to the weight of Exel I-Beam per linear metre is lighter than cold-formed stainless steel (316) I-Beam. Therefore, the truck will use less fuel in transporting it to the desired destination. Nevertheless, the shortcoming of Exel I-Beam is in the manufacturing process where its embodied energy is 66% higher than cold-formed stainless steel (316) I-Beam. At the end-of-life or the disposal life cycle stage of cold-formed stainless steel (316) I-Beam performs better than Exel I-Beam. This was because an assumption was made that 70% of the stainless steel could be recycled, whereas Exel I-beam was assumed as 100% landfill. Therefore, the embodied energy for cold-formed stainless steel (316) I-Beam at this stage is -0.6 kg CO_{2eq}. This indicates that energy is gained back from the recycling process by 0.6 kg CO_{2eq}. Exel I-Beam gains an embodied energy value of 0.4 kg CO_{2eq} from the landfill process.

Overall, the total embodied energy results for the life cycle of the cold-formed stainless steel (316) I-Beam is 20 kg CO_{2eq} per linear metre whereby the embodied energy of Exel I-Beam is 6 kg CO_{2eq} per linear metre. Figure 6.12 shows that the embodied energy for the life cycle of a linear metre I-Beam can be reduce by 70% when it is fabricated from the pultruded fibre composite instead of the cold-formed stainless steel (316). This dramatic reduction occurs at the material stage and is due to the embodied energy being 80% higher for the cold-formed stainless steel (316) I-Beam than that of the pultruded fibre composite.

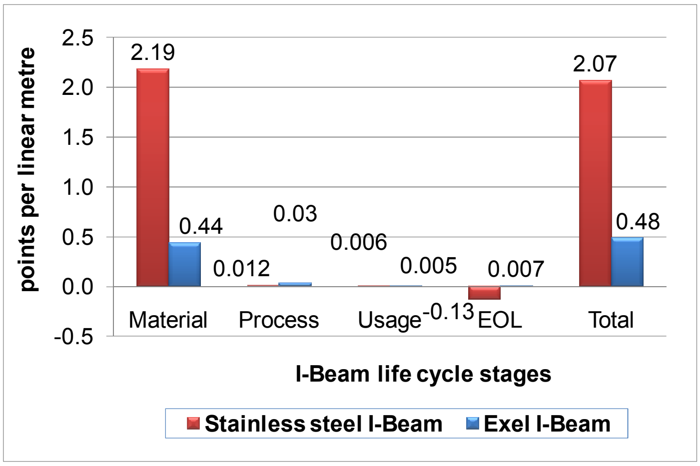


Figure 6.13: Comparison of the embodied energy of an I-Beam made from two different materials measuring 1 linear metre using the Eco-Indicator99 H/A version 2.03 method

Figure 6.13 presents the total environmental impacts using the Eco-Indicator 99 H/A version 2.03 method as stated in Section 6.2.2. This is a full Life Cycle Assessment analysis as it calculates the environmental impacts that have an effect towards human health, the ecosystem quality and resource use. The calculation takes into account all emission substances such as airbourne and waterbourne emissions. These impacts are then calculated into a single score which is expressed in a unit of points.

The total environmental impacts of the I-Beams at the material life cycle stage are 2.1 points per linear metre for the cold-formed stainless steel (316) I-Beam and 0.5 points per linear metre for Exel I-Beam. This 77% reduction is due to the fact that a relatively high amount of energy is required during the extraction process of the metals included in making stainless steel (316) such as chromium and manganese. Therefore, large amount of emission substances are emitted, which subsequently cause high environmental impacts.

Another advantage of Exel I-Beam is found at the usage stage in Figure 6.13 where the environmental impacts are reduced by 16% during the installation activities. This is due to the Exel I-Beam being lighter than the cold-formed stainless steel (316) I-Beam. Therefore, the truck will use less fuel in transporting it to the desired destination.

Nevertheless, the shortcoming of Exel I-Beam is in the manufacturing process where its embodied energy is 60% higher than cold-formed stainless steel (316) I-Beam.

However, the end-of-life or the disposal life cycle stage for the cold-formed stainless steel (316) I-Beam performs better than the pultruded fibre composite I-Beam. This was because an assumption was made that 70% of the stainless steel could be recycled, whereas Exel I-Beam was assumed as 100% landfill. Therefore, the embodied energy for the cold-formed stainless steel (316) I-Beam at this stage is -0.13 points. This indicates that advantage of the recycling process which helps to reduce the environmental impacts by 0.13 points. Exel I-Beam gains an embodied energy of 0.007 points from the landfill process.

Overall, the total environmental impacts results for the life cycle of the cold-formed stainless steel (316) I-Beam is 2 points per linear metre, compared to the total environmental impacts of the pultruded fibre composite which is 0.5 points per linear metre. Figure 6.13 shows that the total environmental impacts for the life cycle of a linear metre I-Beam can be reduced by 76% when it is fabricated from the pultruded fibre composite instead of the cold-formed stainless steel (316). This substantial reduction occurs at the material stage and is due to the embodied energy being 80% higher for the cold-formed stainless steel (316) I-Beam than that of the pultruded fibre composite.

According to the results presented in Figures 6.11 to 6.13, a linear Exel I-Beam manufactured from pultruded fibre composite has a significantly lower embodied energy value than a cold-formed stainless steel (316) I-Beam of the same length. The gained benefits in making an I-Beam out of pultruded fibre composite rather than cold-formed stainless steel (316) are described in the following three points.

- In terms of the energy consumption, an I-Beam that is made from pultruded fibre composite can reduce its energy consumption during its life cycle by up to 50%.
- An I-Beam that is made from pultruded fibre composite can reduce the amount of greenhouse gases emitted into the atmosphere by 70% during its life cycle.
- The total environmental impacts that can effect human health, the ecosystem quality and resource use are reduced significantly by 76%.

On the whole, these benefits are mainly gained during the material stage of the I-Beam life cycle. This is because Exel I-Beam uses significantly less extraction energy than one made from stainless steel (316). However, Exel I-Beam has a higher embodied energy than the cold-formed stainless steel (316) I-Beam at the manufacturing process stage and the end-of-life stage due to the different disposal options.

6.6 Conclusion

This chapter presented the cradle-to-factory and cradle-to-grave analyses which assessed the embodied energy for the raw materials of the pultruded fibre composite and the I-Beams that are made from pultruded fibre composite and stainless steel (316).

The methodology overview was presented by defining the scopes and assumptions of the input data which was required for the calculation of the embodied energy analysis. The Life Cycle Assessment method was selected to calculate the embodied energy of the raw materials and the two different I-Beams. This assessment produced the two embodied energy results and the full Life Cycle Assessment result. They were the primary energy consumption, the greenhouse gas emissions and the total environmental impacts.

These results were expressed in a unit of MJ_{eq}, kg CO_{2eq} and points respectively. The MJ_{eq} and kg CO_{2eq} results were the generic embodied energy values, however these two units only consider the primary energy consumptions and the greenhouse gas emissions. Therefore, the points results were generated from the full Life Cycle Assessment which covers all emission substances that can affect the environment in terms of human health, ecosystem and resource (fossil fuels and mineral) use.

Thereafter, the description of the raw materials and the two different I-Beams was specified. Consequently, the input data of the cradle-to-factory and cradle-to-grave analyses was determined on the basis of the scopes, assumptions and descriptions.

The embodied energy results of the cradle-to-factory analysis demonstrated that the raw materials of a kilogram of pultruded fibre composite gave the embodied energy of 26 MJ_{eq}, 1.23 kg CO_{2eq} and 0.13 points. These results consist of 79% to 87%from the raw material extraction and 13% to 21% from the transportation of the raw materials. The suggestions for reducing the embodied energy of the pultruded fibre composite were given in two different directions. They were using low embodied energy raw materials and choosing the suppliers that use a delivery transportation method that has a low embodied energy.

Subsequently, a hot spots analysis was performed to identify the raw materials or the suppliers that have significantly high embodied energy. The embodied energy of the raw materials (M3) and (9) are significantly higher than other raw materials followed by (M4), (M14), (M8), (M6), (M5) and (M7). Moreover, the transportation of the raw materials of (M3), (M8), (M9) and (M14) are also substantially high. Some recommendations were given such as change to local manufacturers and avoiding as practically as possible the use of road transportation by leaning towards water and rail transportation. The embodied energy results for the whole life cycle of a linear metre Exel I-Beam and a linear metre cold-formed stainless steel (316) I-Beam were assessed using the cradle-to-grave analysis. These results illustrated that the embodied energy of Exel I-Beam is considerably lower than the cold-formed stainless steel (316) I-Beam. This is owing to the significant reduction in energy needed to extract the raw material during the material stage. Moreover, Exel I-Beam is lighter than the cold-formed stainless steel (316) I-Beam, therefore, the fuel consumption to transport the material is proportionally reduced during the installation phase of the usage stage. These advantages largely outweigh the disadvantages of utilising pultruded fibre composite which came from a higher embodied energy value during the manufacturing process stage and the end-of-life stage.

The total embodied energy results of the two I-Beam life cycles revealed that:

- An I-Beam that is made from the pultruded fibre composite consumes 50% less energy during its life cycle than a cold-formed stainless steel (316) I-Beam.

- An I-Beam that is made from the pultruded fibre composite emits 70% less greenhouse gases during its life cycle compared to a cold-formed stainless steel (316) I-Beam.

- An I-Beam that is made from the pultruded fibre composite has an environmental impact which is 76% less than that of a cold-formed stainless steel (316) I-Beam. This equates to a lessening on the effects towards human health, the ecosystem quality and resource use during its life cycle.

CHAPTER 7

WAGNERS CFT MANUFACTURING PTY LTD – EMBODIED ENERGY OF POWER-POLE CROSS-ARM

7.1 Introduction

Power-pole cross-arms are used to support the electrical distribution network as presented in Figure 7.1. Traditionally, power-pole cross-arms are made of conventional materials such as hardwood timber. This is due to the fact that they have the required physical properties such as good insulation and resistance to corrosion.

Alternatively, Wagners CTF Manufacturing Pty Ltd manufactures composite power-pole cross-arms that are made of a fibre composite. The material has similar properties to that of a power-pole cross-arm made from wood. However, it differs in that it is lighter, more durable and also eliminates pole top fires[*]. Moreover, it will not rot or corrode and its life span can extend up to 40 years[*]. The composite power-pole cross-arm is fabricated by using the pultrusion process which comprises of four main steps, namely reinforcement, pultrusion die, pulling unit and sawing unit.

Figure 7.1: Power-pole cross-arm[3]

[3] http://www.wagner.com.au/Divisions/CompositeFibreTechnologies/tabid/67/language/en-US/Default.aspx

Generally, the fibre composite power-pole cross-arm does have some physical and economical advantages over the traditional materials. However, in terms of their environmental performance, it is not so clear and therefore this project aimed to quantify the embodied energy of the fibre composite power-pole cross-arm manufactured from Wagners CTF Manufacturing Pty Ltd.

Therefore, this chapter aims to assess the embodied energy and the environmental impact of the raw materials that are used to make a kilogram of fibre composite from Wagners CTF Manufacturing Pty Ltd. Moreover, the embodied energy analysis is used to compare a power-pole cross-arm from two different materials measuring 2.5 linear metres, namely the fibre composite and the sawn hardwood. Life Cycle Assessment is used as a tool to calculate the embodied energy of a kilogram of fibre composite and the two different power-pole cross-arms.

Cradle-to-factory analysis is used in this chapter to determine the embodied energy and the total environmental impacts of the raw materials required to make a kilogram of the fibre composite. This material is used by Wagners CTF Manufacturing Pty Ltd to produce a power-pole cross-arm. In addition, cradle-to-grave analysis is employed to compare the embodied energy and the total environmental impacts of the life cycle of 2.5 linear metres power-pole cross-arms, which are made of the fibre composite and hardwood timber. Theoretically, cradle-to-grave analysis is an assessment of a product life cycle including the raw material extraction, manufacturing process, usage, transportation and end-of-life.

The outline of this chapter is as follows:

- Methodology overview of the cradle-to-factory and cradle-to-grave analyses
- General scopes and assumptions of the analyses
- Description of a kilogram of fibre composite
- Description of a 2.5 linear metres of a power-pole cross-arm that is made from the fibre composite and the sawn hardwood
- Input data of the cradle-to-factory and cradle-to-grave analyses
- Cradle-to-factory results and discussion: the embodied energy of the raw materials require to make a kilogram of the fibre composite
- Cradle-to-grave results and discussion: the comparison between a 2.5 linear metres power-pole cross-arms that is made from the fibre composite and the sawn hardwood.
- Conclusion is drawn in the last section of the chapter

7.2 Methodology Overview

7.2.1 Embodied energy analysis

In this study, the embodied energy analysis of a power-pole cross-arm comprises of cradle-to-factory and cradle-to-grave analyses as shown in Figure 7.2. These analyses employ the Life Cycle Assessment method to assess the environmental impacts of all life cycle stages as shown in Figure 7.2.

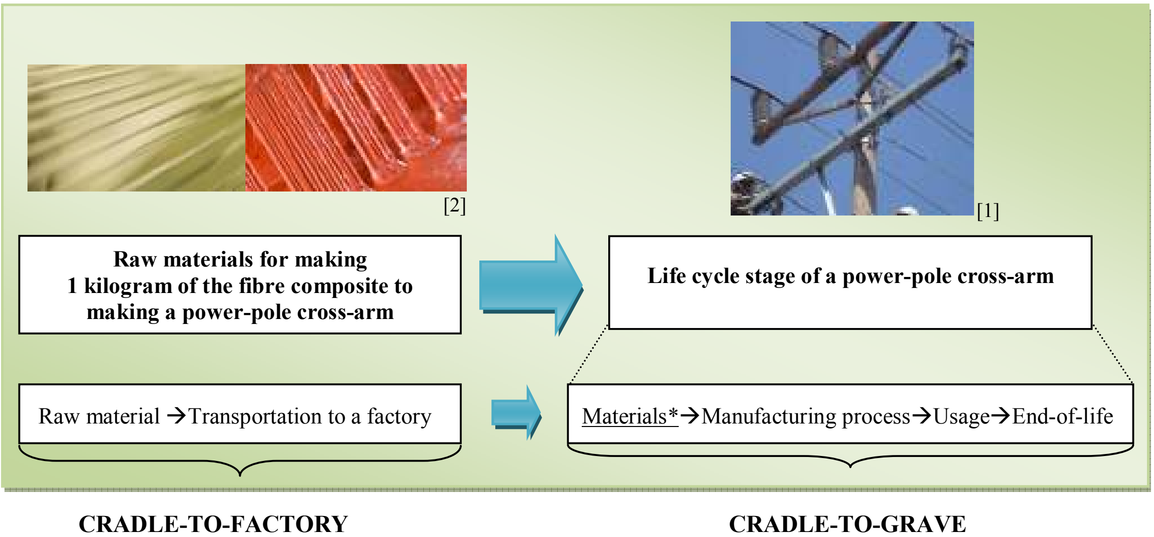


Figure 7.2: Scopes of the cradle-to-factory and cradle-to-grave analyses

The methodology of these two analyses is described briefly as follows. Firstly, the cradle-to-factory analysis assesses the embodied energy and the total environmental impacts in making a kilogram of the fibre composite as presented in the left portion of Figure 7.2. This analysis focuses on two main embodied energy sources. They are the raw material extraction and the transportation of raw materials from the supplier to a factory, i.e. Wagners CTF Manufacturing Pty Ltd. The asterisk sign next to the word 'Materials' in Figure 7.2 indicates that the embodied energy result from this analysis will be used as the input data for the materials stage in the next analysis.

Secondly, the cradle-to-grave analysis as shown in Figure 7.2 calculates the life cycle of a fibre composite power-pole cross-arm with a dimension of 2.5 linear metres. For comparison purposes this analysis technique is also performed on a hardwood timber power-pole cross-arm with the same length. The life cycle stages of these products are presented on the right hand side of Figure 7.2 where:

- The materials stage is the total raw materials that are used in making the power-pole cross-arms;
- The manufacturing process stage comprises the processes involved in making the power-pole cross-arms;

- The usage stage consists of the activities that occur after the power-pole cross-arm is manufactured i.e. the installation and maintenance activities, until the product is disposed of. In this case, the usage period is 40 year where the distribution and the replacement activities are considered;
- The end-of-life stage is the disposal scenario which includes the transportation of the power-pole cross-arms to the disposal site and the disposal process.

Finally, the embodied energy results from the cradle-to-factory analysis are discussed and the hot spots identified. For this project a hot spot is defined as the raw materials and/or suppliers which have a high contribution to the embodied energy results. The hot spots analysis was conducted in order to make further suggestions in order to minimise or eliminate the identified raw materials and/or suppliers. Subsequently, the embodied energy results of the fibre composite power-pole cross-arm from the cradle-to-grave analysis are analysed and compared with the life cycle of the hardwood timber power-pole cross-arm.

7.2.2 Scopes and assumptions of the embodied energy analysis

This section presents Tables 7.1 and 7.2 to clarify the scopes and assumptions that were made for the cradle-to factory and the cradle-to-grave analyses. Table 7.1 provides the main scope of the cradle-to-factory analysis which focuses in quantifying the embodied energy of the raw materials in making a kilogram of the fibre composite. Subsequently, the scopes of the input data that are associated with the raw material extraction and their transportation are given in Table 7.1. Furthermore, Table 7.1 shows the data sources that are used to make the assumptions for the input data of the cradle-to-factory analysis. Overall, the input data in terms of the quantities and the types of materials and transportation were provided by Wagners CTF Manufacturing Pty Ltd. The rest of the data was obtained by using further literature reviews and the libraries from the database of the LCA software, SimaPro 7.1.8.

For instance, the input data for the amount of raw material was based on the information from the Material Safety Datasheets (MSDs) which were provided by Wagners CTF Manufacturing Pty Ltd. The material types were assumed using the Australian Data 2007 (AU) library and the distance of the transportation of raw materials was found using the online maps provided by Google.

<table>
<tr><th colspan="6">CRADLE-TO-FACTORY</th></tr>
<tr><td colspan="6">Scope: To quantify the embodied energy of the raw materials in making 1 kilogram of the fibre composite.</td></tr>
<tr><td>Input data</td><td colspan="5">Amount of the raw materials used in making 1 kilogram of the fibre composite.</td></tr>
<tr><th rowspan="2">Material life cycle stage</th><th rowspan="2">Scopes and assumptions</th><th colspan="4">Data sources</th></tr>
<tr><td>WA</td><td>LR</td><td>AU</td><td>ID</td></tr>
<tr><td rowspan="2">Raw material extraction</td><td>Amount of raw materials (kg)</td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>Material types</td><td>✓(MSDs)</td><td></td><td>✓</td><td>✓</td></tr>
<tr><td rowspan="3">Transportation of raw materials:
From: Suppliers
To: Wagners CTF Manufacturing Pty Ltd (Queensland)</td><td>The locations of suppliers</td><td>✓</td><td>✓</td><td></td><td></td></tr>
<tr><td>Distance (km): Measure by using the online maps</td><td></td><td>✓</td><td></td><td></td></tr>
<tr><td>Transportation types</td><td>✓</td><td>✓</td><td>✓</td><td></td></tr>
</table>

Note:Wagners CTF Manufacturing Pty Ltd (WA), Literature review (LR),the 'Australia data 2007'(AU), the 'Data archive' (DA) the 'ETH-ESU 96' (ET),and the 'IDEMAT2001'(ID) libraries are the databases from the SimaPro 7.1.8 software.

Table 7.1: Scopes and assumptions of the cradle-to-factory analysis

Similarly, Table 7.2 presents the scopes of the cradle-to-grave analysis for the life cycle of the two power-pole cross-arms during the life span of 40 years. The life cycle input data in terms of the quantities and types are assumed based on the data sources as shown in the table.It is worth highlighting the assumption for the material stage of the fibre composite power-pole cross-arm in Table 7.2. The material stage has two embodied energy sources. They are the raw material extraction and the transportation of those materials.

In this stage, the embodied energy of the power-pole cross-arm is assumed to be calculated directly from the embodied energy results of the cradle-to-factory analysis. The calculation is carried out by multiplying the embodied energy results from the cradle-to-factory analysis which is produced in the unit of per kg with 9.5 kg per power-pole cross-arm. For instance, the embodied energy result of the raw material extraction from the cradle-to-factory analysis is 14 MJ_{eq} per kg and the weight of the power-pole cross-arm is 9.5 kg per power-pole cross-arm. Therefore, the embodied energy result for the material stage in this cradle-to-grave analysis is:

$$25\ MJ_{eq} \text{ per kg} \times 9.5 \text{ kg per power-pole cross-arm} = 133\ MJ_{eq} \text{ per linear metre}$$

CRADLE-TO-GRAVE							
Scope: To analyse the embodied energy for the life cycle of the 2.5 linear metres power-pole cross-arms that made from the fibre composite and the hardwood timber.							
Life cycle stages of the power-pole cross-arms	**Scopes and assumptions**	**Data sources**					
		WA	LR	AU	DA	ET	ID
Material stage: *Input data of the amount of the raw materials per 2.5 linear metres*	***Fibre composite power-pole cross-arm:***						
	Material type:						
	- Fibre composite: 9.5 kg per 2.5 linear metres	✓	✓	✓			✓
	Multiply the embodied energy results from the cradle-to-factory analysis which is produced in the unit of per kg with 9.5 kg per 2.5 linear metres						
Raw material extraction And Transportation of raw materials:	*- Rolled – Steel: 5kg per 5 connections*	✓		✓	✓		✓
	Hardwood timber power-pole cross-arm:						
	Material type:						
	*- Sawn hardwood**:** 26.38 kg per 2.5 linear metres*	✓	✓	✓			
From: A Supplier *To:* Wagners CTF Manufacturing Pty Ltd	**Distance*:** From Wollongong. Use the online map to measure the distance (km)		✓	✓			
	By*: Articulated truck for freight						
	- Rolled – Steel: 5kg per 5 connections	✓	✓	✓	✓		
Manufacturing process: *Input data*	***Fibre composite Power-pole cross-arm:***						
	Amount: Total Electricity consumption	✓		✓		✓	
	Energy type: Electricity in Victoria			✓			
	Hardwood timber power-pole cross-arm:						
	Process type: Cutting		✓		✓	✓	✓
Usage: *Input data* Installation *From:* Wagners CTF Manufacturing Pty Ltd *To:* A customer	*Both Power-pole cross-arms:* **Distance***: 200km is assumed **By***: Articulated truck for freight			✓			
Usage: *Input data* *Maintenance* *Replacing process at the end of the 20th year*	***Fibre composite power-pole cross-arm:*** *No replacement required.*	✓					
	Hardwood timber power-pole cross-arm: *Required to replace a second set at the end of the 20th year.*	✓		✓			
End-of-life: *Input data* Disposal transportation *From:* A customer *To:* A disposal site	*Both Power-pole cross-arms:* **Distance***: 200km **By***: Articulated truck for freight			✓			
End-of-life: *Input data* Disposal scenarios: Household waste	*Both Power-pole cross-arms:* 100% landfill for fibre composites and sawn hardwood	✓		✓			
	and 70% recycling for steel			✓			

*Note: *Arbitrary assumption is used a standard value for the 'Composites: Calculating their Embodied Energy Study' where 200 km was suggested by one of the participant composite company.*

Wagners CTF Manufacturing Pty Ltd (WA), Literature review (LR),the 'Australia data 2007'(AU), the 'Data archive' (DA) the 'ETH-ESU 96' (ET), and the 'IDEMAT2001'(ID) libraries are the databases from the SimaPro 7.1.8 software.

Table 7.2: Scopes and assumptions of the cradle-to-grave analysis

In addition, certain input data for the life cycle of the two power-pole cross-arms was assumed arbitrarily. This is because there was no input data available as the data will vary depending on the situation. However, it is essential to assume the same value for transportation in order to make a fair comparison. Therefore, 200 kilometres and a articulated truck (i.e. semi trailer) were assumed for the installation, maintenance and disposal transportation for both power-pole cross-arms. Moreover, the 200 kilometres distance was actually based on the input data that was designated by one of the participant companies in this 'Composites: Calculating their Embodied Energy' Study.

The maintenance activity was assumed based on the information from Wagners CTF Manufacturing Pty Ltd. The transportation for the replacing of the hardwood timber power-pole crosee-arm was also assumed as 200 kilometres at the end of the 20th year. Whereby, the fibre composite required no replacement process during the life span of 40 years.

The transportation for the replacing of the hardwood timber power-pole crosee-arm was also assumed as 200 kilometres. Moreover, the 200 kilometre distance was based on the input data that was designated by one of the participant companies in this 'Composites: Calculating their Embodied Energy' Study.

Table 7.3 is given to clarify the scopes and the assumptions of the embodied energy calculation tool which was selected for the cradle-to-factory and the cradle-to-grave analyses. As a result, three Life Cycle Impact Assessment methods from the SimaPro 7.1.8 software were selected as shown in the table. They are the Cumulative Energy Demand version 1.04, the IPCC GWP 100a version 1.00 and the Eco-Indicator 99 H/A version 2.03 methods.

Furthermore, Table 7.3 also summarises the calculation approach and the results of the three methods for the cradle-to-factory and cradle-to-grave analyses. These methods generated the embodied energy results for these analyses in the units of MJ_{eq}, kg CO_{2eq} and points per kg as well as in units of MJ_{eq}, kg CO_{2eq} and points per power-pole cross-arm. Therefore, Figure 7.3 is given to provide additional information to aid in how to interpret these results.

Additionally, the amount of six conventional air pollutants as listed in Table 7.3 are as the total airbourne substances that are emitted during the cradle-to-factory and cradle-to-grave analyses.

<table>
<tr><th colspan="5">EMBODIED ENERGY CALCULATION TOOL</th></tr>
<tr><th>Embodied Energy Analysis</th><th colspan="4">Scopes and Assumptions</th></tr>
<tr><td>Embodied energy assessment tool</td><td colspan="4">The Life Cycle Impact Assessment methods from the LCA software, SimaPro 7.1.8 software.</td></tr>
<tr><td>Selection of the Life Cycle Impact Assessment methods</td><td colspan="4">The selection of these methods was based on the generic embodied energy analysis which is often based on the input-output model that is used to quantify the primary energy sources and often expressed in MJ and in kg of CO_2 units. In addition, as the two values from the Cumulative energy demand version 1.04 and the IPCC GWP 100a version 1.00 methods only represent the embodied energy in terms of the primary energy consumption and the impacts from the climate change respectively. Therefore, the points value is also given. This value is calculated from Life Cycle Assessment which considers the impacts on human health, the ecosystem quality and resource use. The points value is calculated from the Eco-Indicator 99 H/A version 2.03 method.</td></tr>
<tr><th colspan="5">LIFE CYCLE IMPACT ASSESSMENT METHODS</th></tr>
<tr><th rowspan="2">Method</th><th rowspan="2">Calculation Approach and unit</th><th colspan="3">Embodied Energy Results</th></tr>
<tr><th>Cradle-to-factory</th><th>Cradle-to-grave</th><th>Amount of conventional air pollutions</th></tr>
<tr><td>Cumulative energy demand version 1.04</td><td>Calculation: Calculates the embodied energy in terms of the consumption of the primary energy sources such as fossil fuels, minerals, renewable energy.
Unit: MJ_{eq}</td><td>MJ_{eq} per kg</td><td>MJ_{eq} per power-pole cross-arm</td><td rowspan="3">Carbon monoxide (CO)
Carbon dioxide (CO_2)
Nitrogen dioxide (NO_2)
Sulphur dioxide (SO_2)
Unspecified particulate
Volatile organic compounds (VOC)</td></tr>
<tr><td>IPCC GWP 100a version 1.00</td><td>Calculation: Calculates the greenhouse gas emissions which impact the global warming.
Unit: kg CO_{2eq}</td><td>kg CO_{2eq} per kg</td><td>kg CO_{2eq} per power-pole cross-arm</td></tr>
<tr><td>Eco-Indicator 99 H/A version 2.30</td><td>Calculation: calculates as the environmental performance indicator as a single score. This is a comprehensive Life Cycle Assessment analysis which considers human health, the ecosystem quality and resource use impacts.
Unit: points of a single score</td><td>points per kg</td><td>points per power-pole cross-arm</td></tr>
</table>

Table 7.3: The scopes and assumptions for the calculation tools and results of the embodied energy.

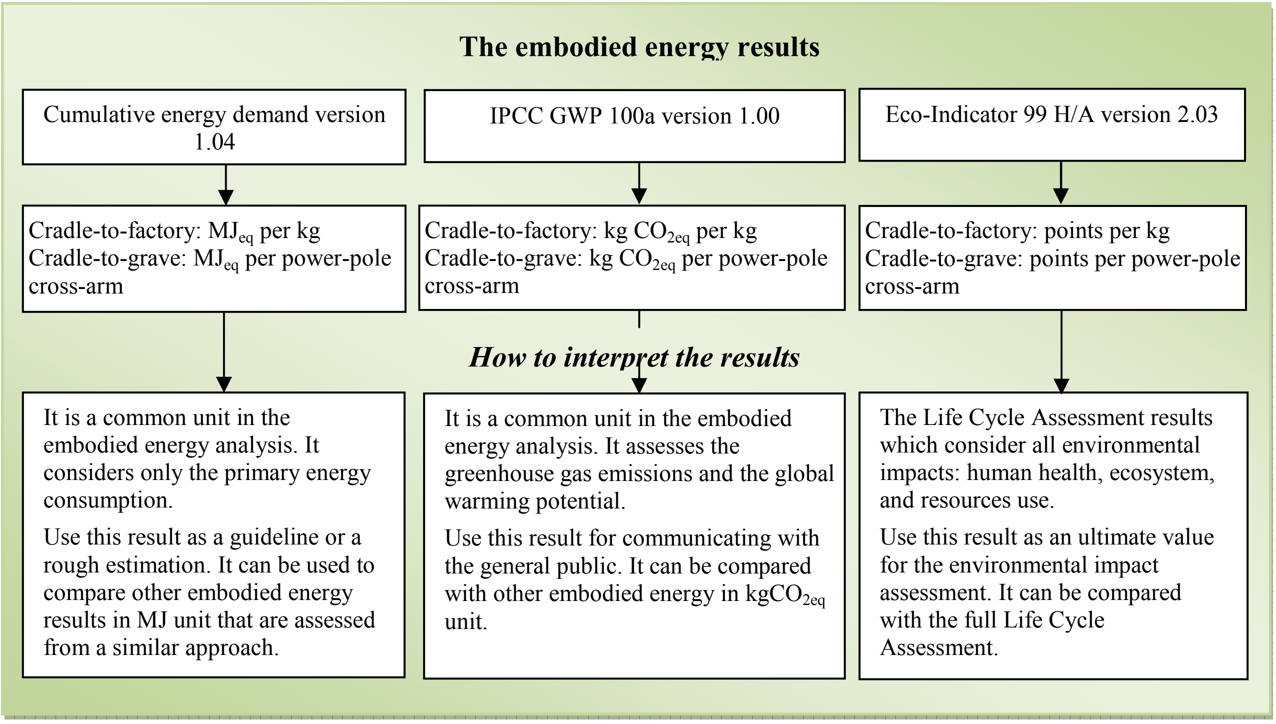


Figure 7.3: How to interpret the embodied energy results.

7.3 Material and Product description

7.3.1 Fibre composite description

The description of the raw materials used in manufacturing of the fibre composites is summarised in Table 7.4. These two raw materials which are fiberglass and plastic resins are equivalent to 95% of the total ingredients. These raw materials are supplied by two suppliers from overseas. The transportation of the raw materials from suppliers to Wagners CTF Manufacturing Pty Ltd located in Queensland involves road and water transportation. The transportation of the raw materials is presented in the last column of Table 7.4.

Additionally, Table 7.4 presents the abbreviations of the raw material type 'M' and its transportation 'M_T' which are provided for later discussion in this chapter. As there are 14 suppliers involved in this analysis, M1 to M2 and also M1_T1 to M2_T2 present in Table 7.4.

Raw material type	List of raw material	Region of supplier	Road and water transportation of raw material: from a supplier to the factory, Wagners CTF Manufacturing Pty Ltd (Wagn.)
Fibre glass	M1	Asia and overseas	Supplier *(M1) → (M1_T1) → (M1_T2) → Factory (Wagn.)
Resin	M2	Asia and overseas	Supplier *(M2) → (M2_T1) → (M2_T2) → Factory (Wagn.)

Note: The abbreviations of 'M' and "M_T' are provided for the discussion of Figure 7.8.
Raw material types (M), First transportation of the raw material (M_T1) and Second transportation of the raw material (M_T2
(Road transportation such as a truck) and (Water transportation such as an Australian international shipping)

Table 7.4: Raw materials and the transportation of raw materials in making a kilogram of the fibre composite.

7.3.2 A power-pole cross-arm description

The cradle-to-grave analysis focuses on assessing the embodied energy of a power-pole cross-arm measuring 2.5 linear metres. The dimension[4] and weight of the 2.5 linear metres power-pole cross-arms are:

- Fibre composite (100×100×5.2mm) = 9.50 kg per 2.5 linear metre (3.8 kg per linear metre)
- Hardwood timber (100×100) = 26.38 kg per 2.5 linear metre

The hardwood timber power-pole cross-arm dimension was provided by Wagners CTF Manufacturing Pty Ltd. The weight of hardwood timber power-pole cross-arm was calculated using the hardwood density of 1055 kg/m^3 and the density equation of.

$$\text{Density} = \text{mass/volume} \rightarrow \text{mass (kg)} = 1055\ \text{kg/m}^3 \times (0.1\times0.1\times2.5)\ \text{m}^3 = 26.375\ \text{kg}$$

7.4 Input Data

The input data of the cradle-to-grave analysis for the two power-pole cross-arms made from the fibre composite and hardwood timber are presented in Tables 7.5 and 7.6 respectively. This input data was derived from the scopes and assumptions in Section 7.2.2. Therefore, the input data of all life cycle stages

[4] According to the input data from Wagners CTF Manufacturing Pty Ltd., te fibre composite is a pultruded square hollow section (SHS) where as the hardwood timber is a solid section.

are presented in terms of a unit, the amount and the 'material/process description' which represents the material and process types[5].

Life cycle stage	Materials/Processes description	Unit	Amount	Database
Material: Fibre composite	Fibre composite	kg	9.5	Multiply 1kg results from the cradle-to-factory analysis by 9.5
Process: Pultrusion	Total energy for pultrusion process	kWh	28	Australian data 2007
Usage: Installation transportation	5 steel connections (1 kilogram per connection)	kg	5	Data archive
	Articulated truck freight, customisable/AU U: (14.5 kg*200 km/1000)	tkm	2.9	Australian data 2007
End-of-life: Disposal transportation	Articulated truck freight, customisable/AU U: (14.5 kg*200 km/1000)	tkm	2.9	Australian data 2007
End-of-life: 100% landfill	Household waste: 100% landfill for Fibre composite and 70% for steel recycling	%	100	Australian data 2007

Table 7.5: Input data for 2.5 linear metres of a fibre composite power-pole cross-arm

[5] In relation to this, the data sources for the input data of 'Material/process description' and 'Amount' are also given in the last column of Tables 7.5 and 7.6for the reference of the database background.

Life cycle stage	Materials/Processes description	Unit	Amount	Database
Material: Fibre composite	Sawn Hardwood	kg	26.375	Multiply 1kg results from the cradle-to-factory analysis by 9.5
Process: Cutting	Power saw for cutting the end of sawn wood	kWh	0.06375	Australian data 2007
Usage: Installation transportation	5 steel connections (1 kilogram per connection)	kg	5	Data archive
	Articulated truck freight, customisable/AU U: (14.5kg×200km/1000)	tkm	5.275	Australian data 2007
Usage: Replacing new crossarm at the 20th year	Sawn Hardwood	kg	26.375	Australian data 2007
	Power saw for cutting the end of sawn wood	min	0.06375	ESU-ETH 96 and Australian data 2007
	5 steel connections (1 kilogram per connection)	kg	5	Data archive
	Articulated truck freight, customisable/AU U: (31.375kg×200km/1000)	tkm	6.275	Australian data 2007
Disposal transportation for the first set of cross-arm at the 20th year	Articulated truck freight, customisable/AU U: (31.375kg×200km/1000)	tkm	6.275	Australian data 2007
Disposal transportation for the second set of cross-arm at the 40th year	Articulated truck freight, customisable/AU U	tkm	6.275	Australian data 2007
End-of-life:	Household waste: 100% landfill for Fibre composite and sawn hardwood, 70% for steel recycling	%	100	Australian data 2007

Table 7.6: Input data for 2.5 linear metres of a hardwood timber power-pole cross-arm.

7.5 Embodied Energy Results

7.5.1 Cradle-to-factory results and discussion

The cradle-to-factory analysis was carried out by using the Life Cycle Assessment method to assess the embodied energy of the raw materials that are comprised in a kilogram of the fibre composite as presented in Figure 7.4. This assessment produced the embodied energy results in three different environmental aspects. They are the primary energy consumption, the greenhouse gas emissions and the total environmental impacts or a single score. These results are expressed in a unit of MJ_{eq} per kg, kg CO_{2eq} per kg and points per kg respectively. These charts display the results in terms of the raw material extraction and the transportation of the raw materials from suppliers to Wagners CTF Manufacturing Pty Ltd as depicted in Table 7.4. The last bar of the charts gives the total results of the two main embodied energy sources which are the sum of the raw material extraction and the transportation of the raw materials.

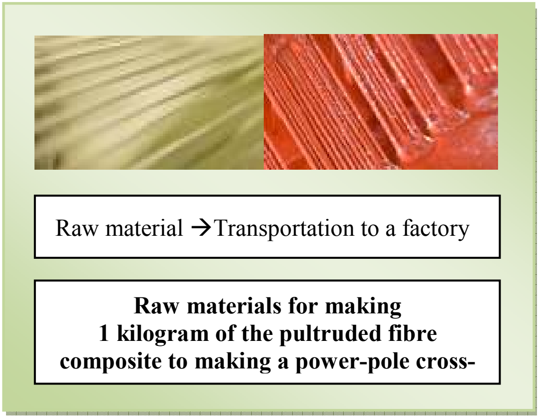


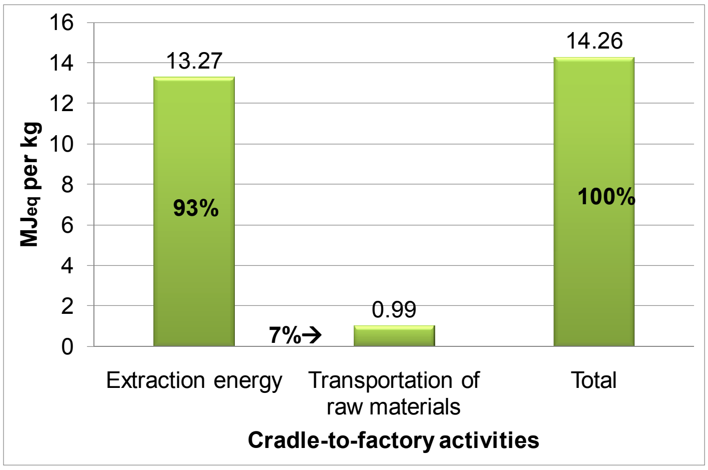
Figure 7.4: Two main embodied energy sources of the cradle-to-factory analysis

The total results of these two embodied energy sources are also provided in the last bar of Figures 7.5 (a) to (c). On the whole, the raw materials for a kilogram of fibre composite give a total embodied energy results of 14 MJ_{eq} per kg, 0.6 kg CO_{2eq} per kg and 0.08 points per kg.

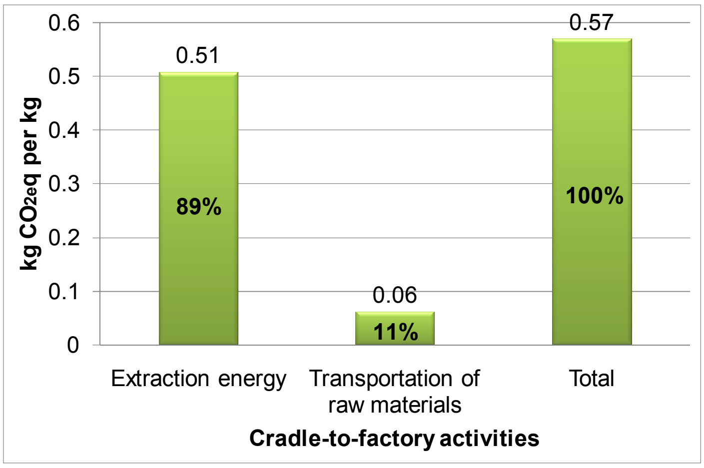
These results consist of 89% to 94% from the raw material extraction and 6% to 11% from the transportation of the raw materials as labelled in Figure 7.5. The distinct contributions of the two embodied energy sources are clearly revealed. The finding suggests that the embodied energy of the fibre composite can be reduced in two different directions.

The first direction is to reduce the high embodied energy of the raw material extraction by using alternative raw materials with low embodied energy. The second direction is to be selective in choosing the suppliers in order to ensure low embodied energy in their delivery transportation. Ideally, the first direction would be the best option as it can reduce the embodied energy dramatically by changing some of the raw materials as the raw material extraction actually contributes a large portion in the total embodied energy result.

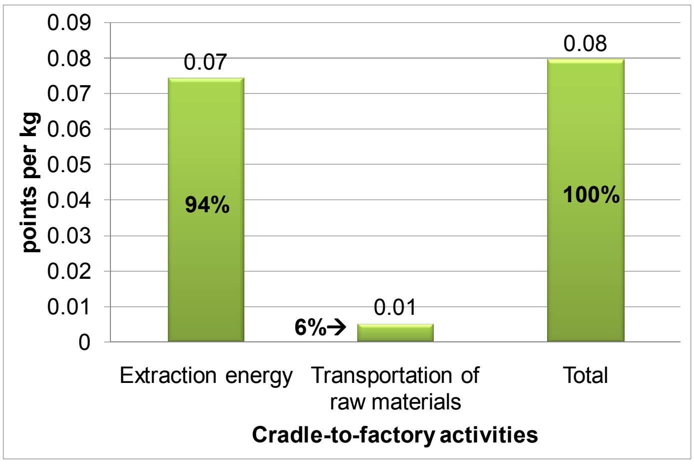
However, it requires further research and development in finding an alternative or a new raw material which requires further investment of the supporting systems. Therefore, this direction can only be targeted as a long term product development plan. In practice, the second direction would be more attractive as it is a fast and a simple approach which requires only a careful consideration in selecting the suppliers. For instance, the selected suppliers should supply the raw materials that are manufactured locally or require less energy-intensive transportation system for transporting the raw materials.



(a) Primary energy consumption results in MJ_{eq} per kg



(b) Greenhouse gas emission results in kg CO_{2eq} per kg



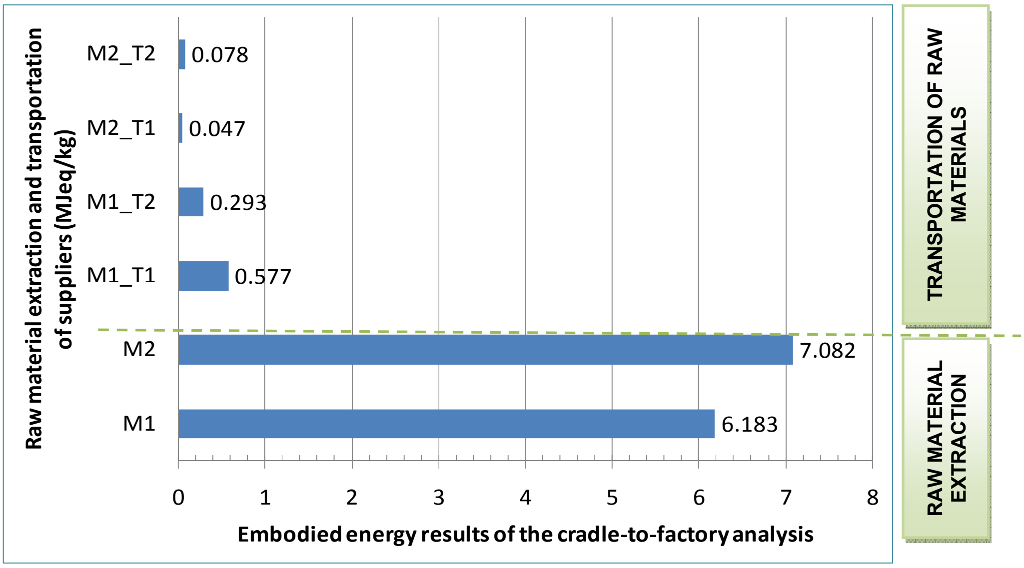
(c) Total environmental impacts results in points per kg

Figure 7.5: Cradle-to-factory results for the fibre composites of Wagners CTF Manufacturing Pty Ltd.

To enhance the implementation of these suggestions, Figure 7.6 explicitly presents the embodied energy for each raw material and its corresponding transportation method. These results are produced from the detailed input data such as the MSDs and the actual location of the suppliers for all raw materials provided by Wagners CTF Manufacturing Pty Ltd.

Figure 7.6 reveals that the embodied energy of the fibre composite from Wagners CTF Manufacturing Pty Ltd was dominated by the combination of several raw materials which originated from overseas suppliers. As a result, a number of hot spots which are the raw materials or the suppliers that have significantly high values are revealed in Figure 7.6.

In this occasion, the raw material (M2) contributes the most followed by the raw material (M1) whereby the obvious hot spots of the supplier's transportation are the transportations of the raw materials (M1) and (M14). Similarly, these higher contributions of the embodied energy for the transportation methods were observed with notable reasons. Since these raw materials were required in high quantities, they needed to be imported from overseas. Therefore a combination of transportation types was utilised.



Note:Raw material types (M), First transportation of the raw material (M_T1), Second transportation of the raw material (M_T2)

Figure 7.6: The detailed embodied energy results (MJ_{eq}/kg) of the cradle-to-factory analysis which displays types and transportation of raw materials

Consequently, these hot spots can be minimised and eliminated by approaching the following recommendations.

- Change the suppliers of the raw material (M1) and (M2) to local manufacturers.
- Improve the transportation system by avoiding to use the road transportation for a long distance.
- Change the transportation types by leaning towards the water and rail transportation

7.5.2 Cradle-to-grave Results and Discussion

As in the cradle-to-grave analysis, the Life Cycle Assessment method was used to assess the embodied energy of the whole life cycle of a 2.5 linear metres fibre composite power-pole cross-arm and a 2.5 linear metres hardwood timber power-pole cross-arm as shown in Figure 7.7. This assessment produced two embodied energy results and the total environmental impact result. They are the primary energy consumption, the greenhouse gas emissions and the total environmental impacts. These results are expressed in a unit of MJ_{eq} per power-pole cross-arm, kg CO_{2eq} per power-pole cross-arm and points per power-pole cross-arm respectively.

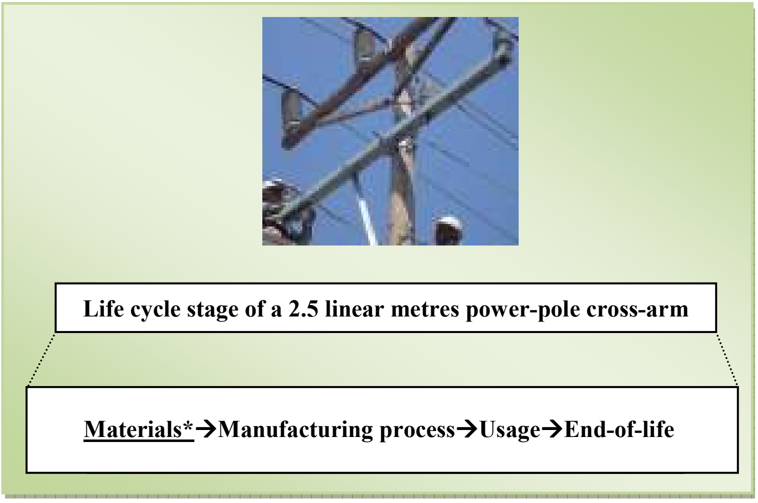


Figure 7.7: The life cycle stages of a 2.5 linear metres power-pole cross-arm (the photo was taken from www.wagner.com.au)

In this section, the three results of the two power-pole cross-arms are presented in Figures 7.8 to 7.10. These charts display the results in terms of the life cycle stages which are the materials, manufacturing process, usage and end-of-life stages as illustrated in Figure 7.7. The last bar of the charts gives the total result of the two power-pole cross-arms which are the sum of the four life cycle stages. The blue bar presents the hardwood timber power-pole cross-arm and the green bar shows the fibre composite power-pole cross-arm.

Figure 7.8 presents the embodied energy results from the perspective of the primary energy consumption which was assessed by the Cumulative Energy Demand version 1.04 method as introduced in Section 7.2.2. The embodied energy of the power-pole cross-arms at the material life cycle stage are 282 MJ_{eq} per power-pole cross-arm for the hardwood timber power-pole cross-arm and 362 MJ_{eq} per power-pole cross-arm for the fibre composite power-pole cross-arm. This equates to a difference of 29% between the two materials. The reason for this is due to the raw materials of the fibre composite came from overseas such as Asia region where use different energy sources to generate the electricity. While, the hardwood timber was produced based on the milling process that uses hydro-electricity and no transportation was included in the database.

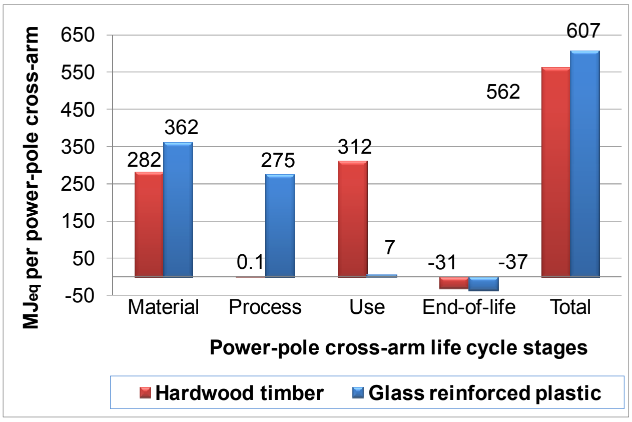


Figure 7.8: Comparison of embodied energy results for the power–pole cross-arms in a unit of MJ_{eq}.

Nevertheless, the advantage of the fibre composite power-pole cross-arm is found at the usage stage in Figure 7.8 where 98% of the fuel consumption is saved during the installation and maintenance activities as this power-pole cross-arm is lighter than the hardwood timber power-pole cross-arm. Nevertheless, the shortcoming of the fibre composite power-pole cross-arm is in the manufacturing process where its embodied energy is considerably higher than the hardwood timber power-pole cross-arm.

However, the end-of-life or the disposal life cycle stage of the fibre composite power-pole cross-arm performs better than the hardwood timber power-pole cross-arm. This was because the fibre composite power-pole cross-arm was assumed to last for 40 years whereby the hardwood timber power-pole cross-arm was assumed to last for 20 years. As a result, the hardwood timber power-pole cross-arm required two sets of the power-pole cross-arm and the five steel connections during the life span of 40 years. Therefore, the hardwood timber power-pole cross-arm consumed twice as much as materials which double the amount of waste went into the disposal process. Therefore, the embodied energy of the hardwood timber power-pole cross-arm at this stage is -31 MJ_{eq} whereas the fibre composite power-pole cross-arm gains an embodied energy value of -38 MJ_{eq}. These two negative results indicate that energy is gained back from the recycling process by 31 MJ_{eq} and 367 MJ_{eq} respectively from the 70% recycling for the steel connections and 100% landfill process for fibre composite and sawn hardwood.

Overall, the total embodied energy results for the life cycle of the hardwood timber power-pole cross-arm is 562.45 MJ_{eq} per linear metre. The embodied energy of the fibre composite is 607 MJ_{eq} per power-pole cross-arm. Figure 7.8 shows that the embodied energy for the life cycle of a 2.5 linear metres power-pole cross-arm can be increased slightly by 8% when it is fabricated from the fibre composite instead of the sawn hardwood. This slightly increase occurs at the material and manufacturing process stages and is due to the embodied energy during the material stage being 59% higher for the fibre composite power-pole cross-arm than that of the sawn hardwood.

Figure 7.9 presents the embodied energy results from the perspective of greenhouse gas emissions. These results were assessed by the IPCC GWP 100a version 1.00 as presented in Section 7.2.2. The embodied energy of the power-pole cross-arms at the material life cycle stage are 114 kg CO_{2eq} per power-pole cross-arm for the hardwood timber power-pole cross-arm and 25 kg CO_{2eq} per power-pole cross-arm for the fibre composite power-pole cross-arm. The difference between the two materials equates to a reduction in greenhouse gas emissions by 78%. The main contribution of this high impact in using the hardwood timber is due to the sawn hardwood has taken into account of the carbon sinks which is when trees or forest helps to remove CO_2 from the atmosphere[1].

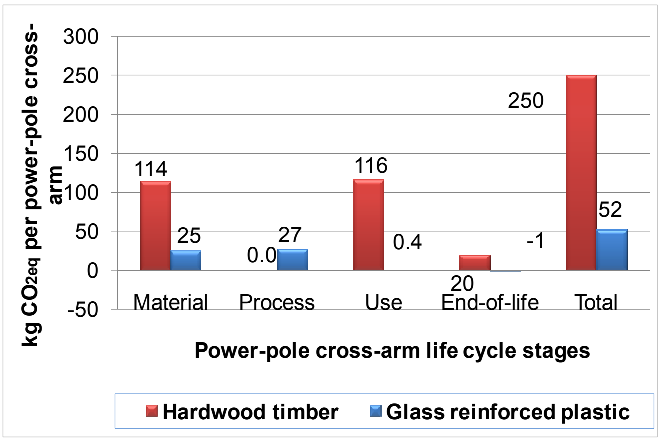


Figure 7.9: Comparison of the embodied energy results of the power-pole cross-arm in a unit of kg CO_{2eq}.

An obvious advantage of the fibre composite power-pole cross-arm is also found at the usage stage in Figure 7.9 where there is a significant reduction in greenhouse gas emissions during the installation and replacement activities. This is due to the weight of the fibre composite per power-pole cross-arm is lighter than the hardwood timber power-pole cross-arm. Therefore, the truck will use less fuel in transporting it to the desired destination. Moreover, as there was no replacement activity required for the fibre composite power-pole cross-arm, significantly amount of materials and energy are reduced from the second set of the power-pole cross-arm which was made by the sawn hardwood. Nevertheless, the shortcoming of the fibre composite power-pole cross-arm is in the manufacturing process where its embodied energy is 26.93% slightly higher than the hardwood timber power-pole cross-arm.

However, the end-of-life or the disposal life cycle stage of the fibre composite power-pole cross-arm performs slightly better than the hardwood timber power-pole cross-arm. The embodied energy for the

[1] The sawn hardwood is based on the Australia Data 2007 database from the Life Cycle Assessment software, SimaPro 7.1.8 software. For this particular case, it is assumed that 1.14 kg CO_2 sunk per tonne of wood production.

fibre composite power-pole cross-arm at this stage is -0.53 kg CO_{2eq}. This indicates that energy is gained back from the steel recycling process by 0.53 kg CO_{2eq}. The hardwood timber power-pole cross-arm has 20 kg CO_{2eq}.

Overall, the total embodied energy results for the life cycle of the hardwood timber power-pole cross-arm is 245 kg CO_{2eq} per power-pole cross-arm whereby the embodied energy of the fibre composite is 52 kg CO_{2eq} per power-pole cross-arm. Figure 7.9 shows that the embodied energy for the life cycle of a 2.5 linear metres power-pole cross-arm can be reduce by 79% when it is fabricated from the fibre composite instead of the hardwood timer.

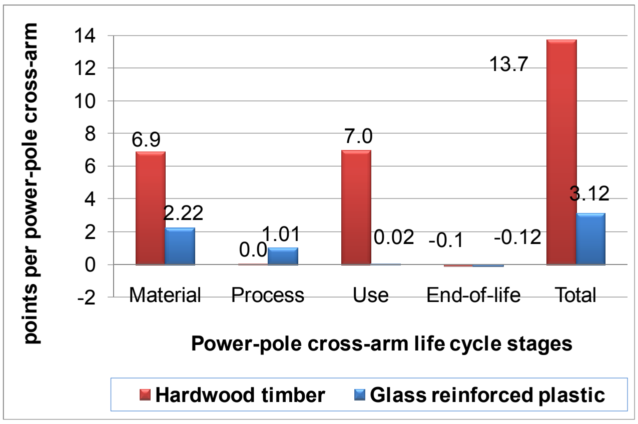


Figure 7.10: Comparison of the embodied energy results of the power-pole cross-arm in a unit of points.

This dramatic reduction occurs at the material and usage stages due to the embodied energy being 78% and 99.62% respectively higher for the hardwood timber power-pole cross-arm than that of the fibre composite.

Figure 7.10 presents the embodied energy results from the perspective of the total environmental impacts using the Eco-Indicator 99 H/A version 2.03 method as stated in Section 7.2.2. This is a comprehensive Life Cycle Assessment analysis as it calculates the environmental impacts that have an effect towards human health, the ecosystem quality and resource use. The calculation takes into account all emission substances such as airbourne and waterbourne emissions. These impacts are then calculated into a single score which is expressed in a unit of points.

The embodied energy of the power-pole cross-arms at the material life cycle stage are 7 points per power-pole cross-arm for the hardwood timber power-pole cross-arm and 2 points per power-pole cross-arm for the fibre composite power-pole cross-arm. This 68% increase for the hardwood timber power-pole cross-arm is due to the fact that the hardwood timber was based on the transforming forest and cutting timber from forest scenario. Therefore, it has a high environmental impact in terms of land use which affects the ecosystem quality in terms of reducing the diversity of biodiversity in the ecosystem. Moreover, a high amount of fuel is required for forest clear cutting activities.

Another advantage of the fibre composite power-pole cross-arm is found at the usage stage in Figure 7.10 where the environmental impacts are reduced by 99.7% during the installation and replacement activities. This is due to the weight of the fibre composite per power-pole cross-arm is lighter than the hardwood timber power-pole cross-arm. Therefore, the truck will use less fuel in transporting it to the desired destination. Moreover, as there was no replacement activity required for the fibre composite power-pole cross-arm, significantly amount of materials and energy are reduced from the second set of the power-pole cross-arm which was made by the sawn hardwood.

Nevertheless, the shortcoming of the fibre composite power-pole cross-arm is in the manufacturing process where its total environmental impact is 99.97% slightly higher than the hardwood timber power-pole cross-arm.

However, the end-of-life or the disposal life cycle stage for the fibre composite power-pole cross-arm performs better than the hardwood timber power-pole cross-arm by 17%. This was because an assumption was made that 70% of the steel could be recycled, whereas the fibre composite power-pole cross-arm was assumed as 100% landfill. Therefore, the total environmental impact for the hardwood timber power-pole cross-arm at this stage is -0.1 points and the fibre composite power-pole cross-arm gains the total environmental impact of -0.12 point. This indicates that energy is gained back from the recycling process by 0.1 and 0.12 point respectively from the recycling process of the steel connections and the landfill process for the fibre composite and sawn hard wood.

Overall, the total environmental impact results for the life cycle of the hardwood timber power-pole cross-arm is 14 points per power-pole cross-arm compared to the total environmental impact of the fibre composite which is 3 points per power-pole cross-arm. Figure 7.10 shows that the embodied energy for the life cycle of a 2.5 linear metres power-pole cross-arm can be reduced by 77% when it is fabricated from the fibre composite instead of the sawn hardwood. This substantial reduction occurs at the material and usage stages of the power-pole cross-arms is due to the embodied energy being 78% and nearly a 100% higher for the hardwood timber power-pole cross-arm than that of the fibre composite power-pole cross-arm.

According to the results presented in Figures 7.8 to 7.10, a power-pole cross-arm manufactured from fibre composite and measuring 2.5 linear metres has a significantly lower embodied energy value than a hardwood timber power-pole cross-arm of the same length. The gained benefits in making a power-pole cross-arm out of fibre composite rather than sawn hardwood are described in the following three points.

- In terms of the energy consumption, a power-pole cross-arm that is made from fibre composite may increase its energy consumption during its life cycle by up to 7%;

- A power-pole cross-arm that is made from fibre composite can reduce the amount of greenhouse gases emitted into the atmosphere by 79% during its life cycle;
- An power-pole cross-arm that is made from the fibre composite causes 77% less environmental impacts that can effect human health, the ecosystem quality and resource use during its life cycle.

On the whole, these benefits are mainly gained during the material stage of the power-pole cross-arm life cycle. This is because the fibre composite uses significantly less extraction energy than one made sawn hardwood. However, the fibre composite power-pole cross-arm has a higher embodied energy than the hardwood timber power-pole cross-arm at the manufacturing process stage and the end-of-life stage due to the different disposal options.

7.6 Conclusion

This chapter presented the cradle-to-factory and the cradle-to-grave analyses which assessed the embodied energy for the raw materials of the fibre composite and the power-pole cross-arms that are made from fibre composite and hardwood timber.

The methodology overview was presented by defining the scopes and assumptions of the input data which was required for the calculation of the embodied energy analysis. The Life Cycle Assessment method was selected to calculate the embodied energy of the raw materials and the two different power-pole cross-arms. This assessment produced the two embodied energy results and the full Life Cycle Assessment result. They were the primary energy consumption, the greenhouse gas emissions and the total environmental impacts.

These results were expressed in a unit of MJ_{eq}, kg CO_{2eq} and points respectively. The MJ_{eq} and kg CO_{2eq} results were the generic embodied energy values, however these two units are only considered the primary energy consumptions and the greenhouse gas emissions. Therefore, the points results were generated from the full Life Cycle Assessment which covers all emission substances that can affect the environment in terms of human health, ecosystem and resource (fossil fuels and mineral) use.

Thereafter, the description of the raw materials and the two different power-pole cross-arms was specified. Consequently, the input data of the cradle-to-factory and cradle-to-grave analyses was determined on the basis of the scopes, assumptions and descriptions.

The embodied energy results of the cradle-to-factory analysis demonstrated that the raw materials of a kilogram of fibre composite gave the embodied energy of 14 MJ_{eq}, 0.57 kg og CO_{2eq} and 0.079 points points. These results consist of 89.09% to 93.55% from the raw material extraction and 6% to 11% from the transportation of the raw materials. The suggestions for reducing the embodied energy of the fibre composite were given in two different directions. They were using low embodied energy raw materials and choosing the suppliers that use a delivery transportation method that has a low embodied energy.

Subsequently, a hot spots analysis was performed to identify the raw materials or the suppliers that have significantly high embodied energy. The embodied energy of the raw materials (M2) is significantly higher than the raw materials (M2). However, the opposite was true as the transportation of the raw materials (M1) is considerably higher than the transportation of the raw materials (M2). Some recommendations were given such as change to local manufacturers and avoiding as practically as possible the use of road transportation by leaning towards water and rail transportation.

The embodied energy and the total environmental impact results for the whole life cycle of a 2.5 linear metres fibre composite power-pole cross-arm and a 2.5 linear metres hardwood timber power-pole cross-arm were assessed using the cradle-to-grave analysis. These results illustrated that the embodied energy of the fibre composite power-pole cross-arm is considerably lower than the hardwood timber power-pole cross-arm. This is owing to the significant reduction in energy needed to extract the raw material during the material stage. Moreover, the fibre composite power-pole cross-arm is lighter than the hardwood timber power-pole cross-arm, therefore, the fuel consumption to transport the material is proportionally reduced during the installation phase of the usage stage. These advantages largely outweigh the disadvantages of utilising pultruded fibre composite which came from a higher embodied energy value during the manufacturing process stage and the end-of-life stage.

The embodied energy and the total environmental impact results of the two power-pole cross-arm life cycles revealed that:

- A power-pole cross-arm that is made from the fibre composite consumes 7% more energy during its life cycle.
- A power-pole cross-arm that is made from the fibre composite emits 79% less greenhouse gases during its life cycle compared to a hardwood timber power-pole cross-arm.
- A power-pole cross-arm that is made from the fibre composite has an environmental impact which is 77% less than that of a hardwood timber power-pole cross-arm. This equates to a lessening on the effects towards human health, the ecosystem quality and resource use during its life cycle.

CHAPTER 8

BOEING RESEARCH AND TECHNOLOGY AUSTRALIA– EMBODIED ENERGY OF AIRCRAFT HINGE FITTING

8.1 Introduction

Aircraft hinge fittings are traditionally made of conventional metals such as titanium which are commonly fabricated by the cold-transforming process. This is due to the fact that they have the required mechanical and physical properties such as their stiffness, strength and lightness.

Alternatively, Boeing Research and Technology Australia manufactures aircraft hinge fittings that are made of a composite material which is a carbon fibre composite. The material has similar properties to that of an aircraft hinge fitting made from titanium. However, it differs in that it is lighter and has a lower material cost.

Figure 8.1: Aircraft.

Ultimately, the material selection for an aircraft hinge fitting depends on the structural integrity, the capital investment and environmental requirement of the application. The carbon fibre composite does have some physical and economical advantages over the traditional materials. However, in terms of their environmental performance, it is not so clear and therefore this project aimed to quantify the embodied energy of the carbon fibre aircraft hinge fitting manufactured by Boeing Research and Technology Australia.

To quantify the environmental impact, many environmental assessment methods have been developed including the embodied energy and Life Cycle Assessment analysis. The embodied energy analysis is commonly used as an ecological impact which is derived from the energy consumption during the manufacturing process of the materials[2]. The common units of the embodied energy are MJ (Mega joule) and kg CO_{2eq} (kilogram of carbon dioxide equivalent). Life Cycle Assessment is a widely used method in calculating the environmental impact of a product life cycle which includes not only the material stage but also the manufacturing process, usage and end-of-life stages.

Therefore, this chapter aims to assess the embodied energy and the environmental impact of the raw materials that are used to make a kilogram of carbon fibre composite from Boeing Research and Technology Australia. Moreover, the embodied energy analysis is used to compare an aircraft hinge fitting made from two different materials, namely carbon fibre composite and the cold-formed titanium. Life Cycle Assessment is used as a tool to calculate the embodied energy of a kilogram of carbon fibre composite and the two different aircraft hinge fittings.

Cradle-to-factory[3] analysis is used in this chapter to determine the embodied energy and the total environmental impacts of the raw materials required to make a kilogram of the carbon fibre composite. This material is used by Boeing Research and Technology Australia to produce an aircraft hinge fitting. In addition, cradle-to-grave analysis is employed to compare the embodied energy and the total environmental impacts of the life cycle of an aircraft hinge fittings, which are made of the carbon fibre composite and the cold-formed titanium. Theoretically, cradle-to-grave analysis is an assessment of a product life cycle including raw material extraction, manufacturing process, usage, transportation and end-of-life.

The outline of this chapter is as follows:

- Methodology overview of the cradle-to-factory and cradle-to-grave analyses
- General scopes and assumptions of the analyses

---

[2] Lawson, B, 1996, Building Materials Energy and the Environment, the Royal Australian Institute of Architects, Canberra, Australia.

[3] Technically, the cradle-to-factory (gate) analysis is commonly defined as "an assessment of a partial product life cycle from manufacture ('cradle') to the factory gate before it is transported to the consumer" (Reference: Moreno, A., 2008, The DEPUIS HANDBOOK Chapter 4: Methodology of Life Cycle Assessment, Accessed: October 2009, http://www.depuis.enea.it/dvd/website.html). However, cradle-to-factory analysis in this project is specified as the embodied energy incurred during the raw material extraction and the transportation from suppliers to manufacturers.

- Description of a kilogram of carbon fibre composite
- Description of an aircraft hinge fitting that is made from carbon fibre composite and cold-formed titanium
- Input data of the analyses
- Cradle-to-factory results and discussion: the embodied energy of the raw materials require to make a kilogram of carbon fibre composite
- Cradle-to-grave results and discussion: the comparison between an aircraft hinge fittings that is made from the carbon fibre composite and the cold-formed titanium.
- Conclusion is drawn in the last section of the chapter

8.2 Methodology Overview

8.2.1 Embodied energy analysis

In this study, the embodied energy analysis of an aircraft hinge fitting comprises of cradle-to-factory and cradle-to-grave analyses as shown in Figure 8.3. These analyses employ the Life Cycle Assessment method to assess the environmental impacts of all life cycle stages as shown in Figure 8.3. The methodology of these two analysis methods is described briefly as follows.

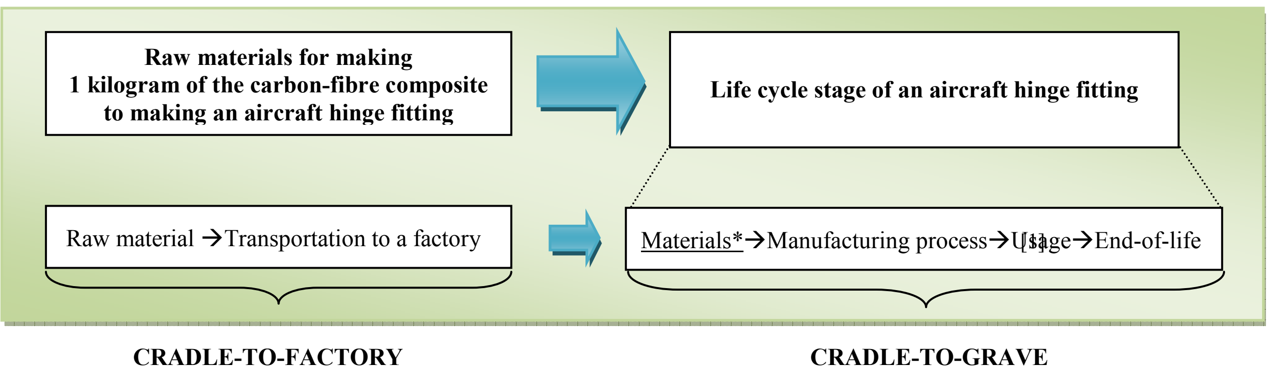


Figure 8.3: Scopes of the cradle-to-factory and cradle-to-grave analyses

The methodology of these two analysis methods are described briefly as follows. Firstly, the cradle-to-factory analysis assesses the embodied energy in making 1 kilogram of the carbon fibre composite as presented in the left portion of Figure 8.3. This analysis focuses on two main embodied energy sources. They are the raw material extraction and the transportation of raw materials from the supplier to a factory, i.e. Boeing Research and Technology Australia. The asterisk sign next to the word 'Materials' in Figure

8.3 indicates that the embodied energy result from this analysis will be used as the input data for the materials stage in the next analysis.

Secondly, the cradle-to-grave analysis as shown in Figure 8.3 calculates the life cycle of an aircraft hinge fitting which made of carbon fibre composite. For comparison purposes this analysis technique is also performed on a titanium aircraft hinge fitting with the same dimension. The life cycle stages of these products are presented on the right hand side of Figure 8.3 where:

- The materials stage is the total raw materials that are used in making the aircraft hinge fittings;
- The manufacturing process stage comprises the processes involved in making the aircraft hinge fitting.
- The usage stage consists of the activities that occur after the aircraft hinge fitting is manufactured i.e. the installation and maintenance activities, until the product is disposed of.
- The end-of-life stage is the disposal scenario which includes the transportation of the aircraft hinge fittings to the disposal site and the disposal process.

Finally, the embodied energy results from the cradle-to-factory analysis are discussed and the hot spots identified. For this project a hot spot is defined as the raw materials and/or suppliers which have a high contribution to the embodied energy results. The hot spots analysis was conducted in order to make further suggestions in order to minimise or eliminate the identified raw materials and/or suppliers. Subsequently, the embodied energy results from the cradle-to-grave analysis of the an aircraft hinge fitting which made of carbon fibre composite are analysed and compared with the life cycle of the titanium aircraft hinge fitting.

8.2.2 Scopes and assumptions of the embodied energy analysis

This section presents Tables 8.1 and 8.2 to clarify the scopes and assumptions that were made for the cradle-to-factory and cradle-to-grave analyses. Table 8.1 provides the main scope of the cradle-to-factory analysis which focuses in quantifying the embodied energy of the raw materials in making a kilogram of the carbon fibre composite. Subsequently, the scopes of the input data that are associated with the raw material extraction and their transportation are given in Table 8.1. Furthermore, Table 8.1 shows the data sources that are used to make the assumptions for the input data of the cradle-to-factory analysis. Overall, the input data in terms of the quantities and the types of materials and transportation were provided by

Boeing Research and Technology Australia. The rest of the data was obtained by using further literature reviews and the libraries from the database of the LCA software, SimaPro 7.1.8.

For instance, the input data for the amount of raw material was based on the information which was provided by Boeing Research and Technology Australia. The material types were assumed using the Australian Data 2007 (AU) library and the distance of the transportation of raw materials was found using the online maps provided by Google. Similarly, Table 8.2 presents the scopes of the cradle-to-grave analysis for the life cycle of the two aircraft hinge fittings. The life cycle input data in terms of the quantities and types are assumed based on the data sources as shown in the table.

<table>
<tr><th colspan="8">CRADLE-TO-FACTORY</th></tr>
<tr><td colspan="8">Scope: To quantify the embodied energy of the raw materials in making 1 kilogram of the carbon fibre reinforced plastic.</td></tr>
<tr><td>Input data</td><td colspan="7">Amount of the raw materials used in making 1 kilogram of the carbon fibre reinforced plastic.</td></tr>
<tr><td rowspan="2">Material life cycle stage</td><td rowspan="2">Scopes and assumptions</td><td colspan="6">Data sources</td></tr>
<tr><td>EX</td><td>LR</td><td>AU</td><td>ET</td><td>ID</td><td>IN</td></tr>
<tr><td rowspan="2">Raw material extraction</td><td>Amount of raw materials (kg)</td><td>✓</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Material types</td><td>✓</td><td></td><td></td><td></td><td>✓</td><td>✓</td></tr>
<tr><td rowspan="3">Transportation of raw materials:
From: Suppliers
To: Boeing Research and Technology Australia (Queensland)</td><td>The locations of suppliers</td><td>✓</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Distance (km): Measure by using the online maps</td><td></td><td>✓</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Transportation types</td><td>✓</td><td></td><td>✓</td><td>✓</td><td></td><td></td></tr>
</table>

Note:Boeing Research and Technology Australia (BR), Literature review (LR),the 'Australia data 2007'(AU), the 'Data archive' (DA), the 'ETH-ESU 96' (ET), and the 'IDEMAT2001'(ID) libraries are the databases from the SimaPro 7.1.8 software.

Table 8.1: The scopes and assumptions of the cradle-to-factory analysis

It is worth highlighting the assumption for the material stage of the carbon fibre composite aircraft hinge fitting in Table 8.2. The material stage has two embodied energy sources. They are the raw material extraction and the transportation of those materials.

In this stage, the embodied energy of the aircraft hinge fitting is assumed to be calculated directly from the embodied energy results of the cradle-to-factory analysis. The calculation is carried out by multiplying the embodied energy results from the cradle-to-factory analysis with 20 kg per aircraft hinge fitting. For instance, the embodied energy result of the raw material extraction from the cradle-to-factory analysis is 367 MJ_{eq} per kg and the weight of the roof tile is 20 kg per aircraft hinge fitting. Therefore, the embodied energy result for the material stage in this cradle-to-grave analysis is:

$$25 \text{ MJ}_{eq} \text{ per kg} \times 20 \text{ kg per aircraft hinge fitting} = 7{,}340 \text{ MJ}_{eq} \text{ per aircraft hinge fitting}$$

In addition, the fuel consumption input data for the usage stage of the two air craft hinge fitting was estimated on a basis of the operation empty weight as suggested by Boeing Research and Technology Australia. This was assumed that the aircraft hinge fitting is part of the operation empty weight of the Boeing 767-200ER, 184,000 lbs which has a average fuel consumption of 1,722 gallon per hour[4]. As a result, the amount of fuel consumption for the carbon fibre and the titanium aircraft hinge fitting were estimated as follows.

Carbon fibre aircraft hinge fitting:

$$41264.78\ \text{gallon} = 1722\frac{gallon}{hour} \times 20000\,flight \times 5\frac{hours}{flight} \times \frac{44.09\ \text{lb}(\text{convertedfrom } 20\text{kg})}{184000\text{lb}}$$

$$112513.8858\,\text{kg} = 41264.78\text{gallon} \times 3.785411784\frac{litres}{gallon} \times \left(0.7203\frac{kg}{litre}\right)_{\text{ker}\,osene\,density}$$

Titanium aircraft hinge fitting:

$$45391.26\ \text{gallon} = 1722\frac{\text{gallon}}{\text{hour}} \times 20000\text{flight} \times 5\frac{\text{hours}}{\text{flight}} \times \frac{48.5016976807\text{lb}(\text{converted from } 22\text{kg})}{184000\text{lb}}$$

$$123765.2744\,\text{kg} = 45391.26\text{gallon} \times 3.785411784\frac{litres}{gallon} \times \left(0.7203\frac{kg}{litre}\right)_{\text{ker}\,osen\,density}$$

The articulated truck was also assumed as the transportation method to the recycling plant at its end-of-life stage.

Table 8.3 is given to clarify the scopes and the assumptions of the embodied energy calculation tool which was selected for the cradle-to-factory and cradle-to-grave analyses. As a result, three Life Cycle Impact Assessment methods from the SimaPro 7.1.8 software were selected as shown in the table. They are the Cumulative Energy Demand version 1.04, the IPCC GWP 100a version 1.00 and the Eco-Indicator 99 H/A version 2.03 methods.

Furthermore, Table 8.3 also summarises the calculation approach and the results of the three methods for the cradle-to-factory and cradle-to-grave analyses. These methods generated the embodied energy results for these analyses in the units of MJ_{eq}, kg CO_{2eq} and points per kg as well as in units of MJ_{eq}, kg CO_{2eq} and points per aircraft hinge fitting. Therefore, Figure 8.4 is given to provide additional information to aid in how to interpret these results. Additionally, the amount of six conventional air

[4] http://www.boeing.com/ids/globaltanker/files/FuelConsReport.pdf

pollutants as listed in Table 8.3 are as the total airbourne substances that are emitted during the cradle-to-factory and cradle-to-grave analyses.

CRADLE-TO-GRAVE									
Scope: To analyse the embodied energy for the life cycle of the aircraft hinge fittings that made from carbon fibre reinforced plastic and cold-formed titanium.									
Life cycle stages	**Scopes and assumptions**	**Data sources**							
		BE	LR	AU	DA	ET	FR	ID	IN
Material stage: *Input data for amount of the raw materials per an aircraft hinge fitting* Raw material extraction And Transportation of raw materials *From:* A Supplier *To:* Boeing Research and Technology Australia	*Carbon fibre aircraft hinge fitting:*								
	- *Carbon fibre reinforced plastic:* 20 kg per aircraft hinge fitting Multiply the embodied energy results from the cradle-to-factory analysis which is produced in the unit of per kg with 20 kg per aircraft hinge fitting	✓	✓	✓		✓		✓	✓
	Cold-formed titanium Aircraft hinge fitting:								
	- *Titanium:* 22 kg per aircraft hinge fitting using	✓						✓	
	400 kg of titanium		✓						
	Distance: - From the United State of America. Use the online map to measure the distance (km)			✓			✓		
	By: Truck (single)-diesel, articulated truck for freight and international shipping								
Manufacturing process: *Input data*	*Carbon fibre aircraft hinge fitting:*								
	Amount: Total Electricity consumption	✓		✓					
	Energy type: Electricity in Victoria	✓							
	Cold-formed titanium Aircraft hinge fitting:								
	- 400 kg is assumed to be cold-transformed.	✓	✓	✓	✓				
	- 378 kg is assumed to be the removed material by the machining process.	✓	✓	✓	✓				
Usage: *Input data* Installation	*Both aircraft hinge fittings:* **Distance***: 25.4 km is assumed								
	By*: Light Commercial Vehicles (freight task)			✓					
Usage: *Input data* Operation	*Both aircraft hinge fittings:* Total fuel consumption of the 20 kg as part of the operation empty weight, 184,000 lb of the Boeing 767-200ER for 20,000 flights of 5 hour per flight at an average fuel consumption of 1,722 gallon per hour								
	Fuel type: Kerosene, Aviation (Mobil oil Australia ATSM4052 at 20 degree, kerosene density of 0.7203kg/litre)	✓	✓	✓					
	20kg of carbon fibre composite Aircraft hinge fitting: **Amount:** 112,513.89 kg	✓	✓	✓					
	22 kg of cold-formed titanium Aircraft hinge fitting: **Amount:** 123,765.27 kg	✓	✓	✓					
End-of-life: *Input data* Disposal transportation *From:* A customer *To:* A disposal site	*Both aircraft hinge fittings:* **Distance***: 200km								
	By*: Articulated truck for freight for the removed material of 378kg and			✓					
	Light Commercial Vehicles (freight task) for the used aircraft hinge fitting			✓					

End-of-life: *Input data* Disposal scenarios	*Carbon fibre aircraft hinge fitting:* **Household waste**: 100% landfill	✓		✓					
	Cold-formed titanium Aircraft hinge fitting: **Household waste**: 100% recycling	✓		✓					

*Note: *Arbitrary assumption is used a standard value for the 'Composites: Calculating their Embodied Energy Study' where 200 km was suggested by one of the participant composite company. Boeing Research and Technology Australia (BE), Literature review (LR), the 'Australia data 2007'(AU), the 'Data archive' (DA) the 'ETH-ESU 96' (ET), the 'Franklin USA 98'(FR), the 'IDEMAT2001'(ID) and the 'Industry Data 2.0' libraries are the databases from the SimaPro 7.1.8 software.*

Table 8.2: Scopes and assumptions of the cradle-to-grave analysis.

EMBODIED ENERGY CALCULATION TOOL				
Embodied Energy Analysis	**Scopes and Assumptions**			
Embodied energy assessment tool	The Life Cycle Impact Assessment methods from the LCA software, SimaPro 7.1.8 software.			
Selection of the Life Cycle Impact Assessment methods	The selection of these methods was based on the generic embodied energy analysis which is often based on the input-output model that is used to quantify the primary energy sources and often expressed in MJ and in kg of CO_2 units. In addition, as the two values from the Cumulative energy demand version 1.04 and the IPCC GWP 100a version 1.00 methods only represent the embodied energy in terms of the primary energy consumption and the impacts from the climate change respectively. Therefore, the points value is also given. This value is calculated from Life Cycle Assessment which considers the impacts on human health, the ecosystem quality and resource use. The points value is calculated from the Eco-Indicator 99 H/A version 2.03 method.			
LIFE CYCLE IMPACT ASSESSMENT METHODS				
Method	**Calculation Approach and unit**	**Embodied Energy Results**		
		Cradle-to-factory	*Cradle-to-grave*	*Amount of conventional air pollutions*
Cumulative energy demand version 1.04 (CED1.04)	*Calculation:* Calculates the embodied energy in terms of the consumption of the primary energy sources such as fossil fuels, minerals, renewable energy. *Unit*: MJ_{eq}	MJ_{eq} per kg	MJ_{eq} per aircraft hinge fitting	Carbon monoxide (CO) Carbon dioxide (CO_2) Nitrogen dioxide (NO_2) Sulphur dioxide (SO_2) Unspecified particulate Volatile organic compounds (VOC)
IPCC GWP 100a version 1.00 (IPCC1.00)	*Calculation:* Calculates the greenhouse gas emissions which impact the global warming. *Unit:* kg CO_{2eq}	kg CO_{2eq} per kg	kg CO_{2eq} per aircraft hinge fitting	
Eco-Indicator 99 H/A version 2.03 (EI992.03)	*Calculation:* calculates as the environmental performance indicator as a single score. This is a comprehensive Life Cycle Assessment analysis which considers human health, the ecosystem quality and resource use impacts. *Unit:* points of a single score	points per kg	points per aircraft hinge fitting	

Table 8.3: The scopes and assumptions for the calculation tools and results of the embodied energy.

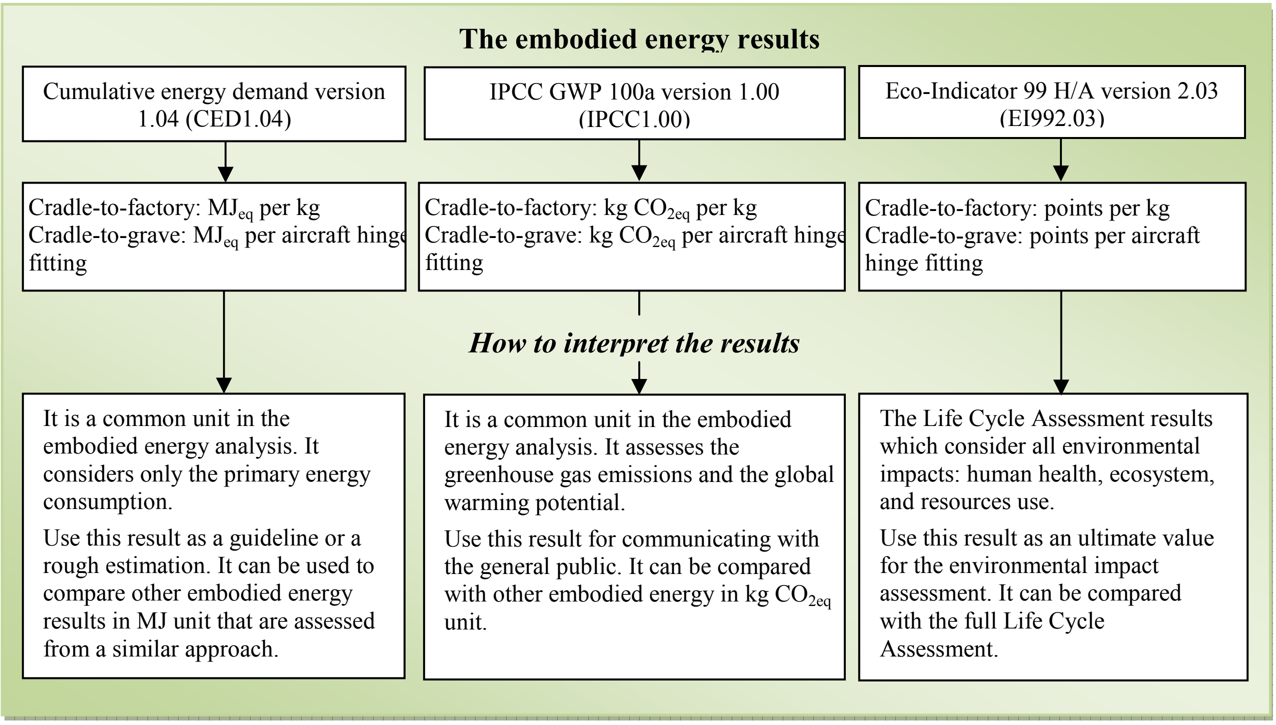


Figure 8.4: How to interpret the embodied energy and the environmental impacts results.

8.3 Material and Product description

8.3.1 Carbon fibre composite description

The description of the raw materials used in manufacturing the carbon fibre reinforced plastic is summarised in Table 8.4. The table presents the abbreviations of the raw material types 'M' which are M1 to M3 and its transportation 'M_T' which are M1_T1 to M3_T3.

Three main raw materials that constitute the carbon fibre reinforced plastic are resin (M3) and carbon fabric (M1+M2) which is made of carbon fibre (M1) and nylon (M2). These raw materials are supplied by four suppliers from Europe. The transportation of the raw materials from suppliers to Boeing Research and Technology Australia located in Victoria involves road and water transportation. Therefore, the transportation of the raw materials is presented in the last column of Table 8.4 for the four suppliers involved in this analysis.

Raw material type	List of raw material	Region of supplier	Road and water transportation of raw material: from a supplier to the factory, Boeing Research and Technology Australia (Exel.)
Carbon fibre Nylon	M1 and M2	Europe	Supplier *(M1 and M2) → (M_T1) → Supplier (M1+2)
Carbon fabric	Supplier (M1+M2) fabricates M1 and M2 into carbon fabric (M1+2)	Europe	Supplier *(M1+2) → (M1+ 2_T1) → (M1+2_T2) → (M1+2_T3) → Factory (Boei.)
Resin	M3	Europe	Supplier *(M3) → (M3_T1) → (M3 _T2) → (M3_T3) → Factory (Boei.)

Note: The abbreviations of 'M' and "M_T' are provided for the discussion of Figure 8.8.
Raw material types (M), First transportation of the raw material (M_T1), Second transportation of the raw material (M_T2) and Third transportation of the raw material (M_T3)
(Road transportation such as a truck) and (Water transportation such as an Australian international shipping)

Table 8.4: Raw materials and the transportation of raw materials in making a kilogram of the carbon fibre reinforced plastic.

8.3.2 An aircraft hinge fitting description

The cradle-to-grave analysis focuses on assessing the embodied energy of an aircraft hinge fitting. The weight of the aircraft hinge fittings are given by Boeing Research and Technology Australia which are:

- Carbon fibre composite = 20 kg per aircraft hinge fitting
- Titanium = 22 kg per aircraft hinge fitting

8.4 Input Data

The input data of the cradle-to-grave analysis for the two aircraft hinge fittings made from the carbon fibre composite and the cold-formed titanium are presented in Tables 8.5 and 8.6 respectively. This input data was derived from the scopes and assumptions in Section 8.2.2. Therefore, the input data of all life cycle stages are presented in terms of a unit, the amount and the 'material/process description' which represents the material and process types.[5]

[5] . In relation to this, the data sources for the input data of 'Material/process description' and 'Amount' are also given in the last column of Tables 8.5 and 8.8for the reference of the database background.

<table>
<tr><th>Life Cycle stage</th><th>Material/process description</th><th>Unit</th><th>Amount</th><th>Data source</th></tr>
<tr><td>Material</td><td>Carbon fibre composite</td><td>kg</td><td>20</td><td>Multiply 1 kg results from the cradle-to-factory analysis by 20</td></tr>
<tr><td rowspan="2">Manufacturing process</td><td>High voltage electricity in Victoria</td><td>kWh</td><td>1,285.30</td><td>Australian Data 2007 LCI library</td></tr>
<tr><td>Fork Lift/AU U</td><td>hr</td><td>1.30</td><td>Australian Data 2007 LCI library</td></tr>
<tr><td>Usage: Installation transportation</td><td>Light Commercial Vehicles (freight task): 0.02 tonne×25.4 km</td><td>tkm</td><td>0.51</td><td>Australian Data 2007 LCI library</td></tr>
<tr><td>Usage: Operation</td><td>Kerosene, Aviation, at consumer/AU U</td><td>kg</td><td>112,513.89</td><td>Australian Data 2007 LCI library</td></tr>
<tr><td>End-of-life: Disposal transportation</td><td>Light Commercial Vehicles (freight task): 0.02 tonne×200 km</td><td>tkm</td><td>4</td><td>Australian Data 2007 LCI library</td></tr>
<tr><td>End-of-life: Disposal process</td><td>Landfill/AU U</td><td>%</td><td>100</td><td>Australian Data 2007 LCI library</td></tr>
</table>

Table 8.5: Input data of a carbon fibre composite aircraft hinge fitting.

<table>
<tr><th>Life Cycle stage</th><th>Material/process description</th><th>Unit</th><th>Amount</th><th>Data source</th></tr>
<tr><td>Material: Raw materials</td><td>Titanium</td><td>kg</td><td>22</td><td>IDEMAT2001</td></tr>
<tr><td rowspan="4">Material: Transportation</td><td>Truck (single) diesel FAL (0.4×2395 km)</td><td>tkm</td><td>3.20</td><td>Franklin 96</td></tr>
<tr><td>Shipping, international freight/AU U (0.4×23,600 km))</td><td>tkm</td><td>9440</td><td rowspan="3">Australian Data 2007 LCI library</td></tr>
<tr><td>Articulated truck freight, customisable/AU U (0.4×27.4 km)</td><td>tkm</td><td>10.96</td></tr>
<tr><td>Articulated truck freight, customisable/AU U (0.022×29.8 km)</td><td>tkm</td><td>0.66</td></tr>
<tr><td rowspan="2">Manufacturing process</td><td>Cold transforming process</td><td>kg</td><td>400</td><td rowspan="2">Data Archive and Australian Data 2007 LCI library</td></tr>
<tr><td>Machining steel DEEDI</td><td>kg</td><td>378</td></tr>
<tr><td>Usage: Installation transportation</td><td>Light Commercial Vehicles (freight task)/AU U : 0.022 tonne×24.5 km</td><td>tkm</td><td>0.5588</td><td rowspan="5">Australian Data 2007 LCI library</td></tr>
<tr><td>Usage: Operation</td><td>Kerosene, Aviation, at consumer/AU U</td><td>kg</td><td>123,765.27</td></tr>
<tr><td rowspan="2">End-of-life: Disposal transportation</td><td>Light Commercial Vehicles (freight task): 0.022 tonne×200 km</td><td>tkm</td><td>4.40</td></tr>
<tr><td>Articulated truck freight, customisable/AU U: 0.378 tonne×200 km</td><td>tkm</td><td>75.60</td></tr>
<tr><td>End-of-life: Disposal process</td><td>Recycling/AU U</td><td>%</td><td>100</td></tr>
</table>

Table 8.6: The input data of a cold-formed titanium aircraft hinge fitting.

8.5 Embodied Energy Results

8.5.1 Cradle-to-factory results and discussion

The cradle-to-factory analysis was carried out by using the Life Cycle Assessment method to assess the embodied energy of the raw materials of a kilogram of the carbon fibre composite as shown in Figure 8.8.

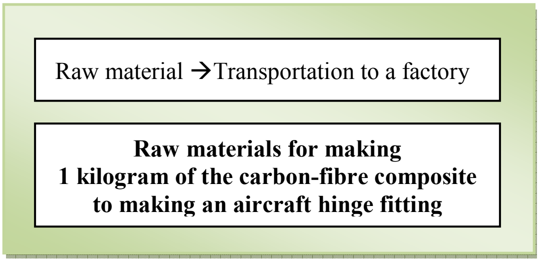


Figure 8.7: Two main embodied energy sources of the cradle-to-factory analysis.

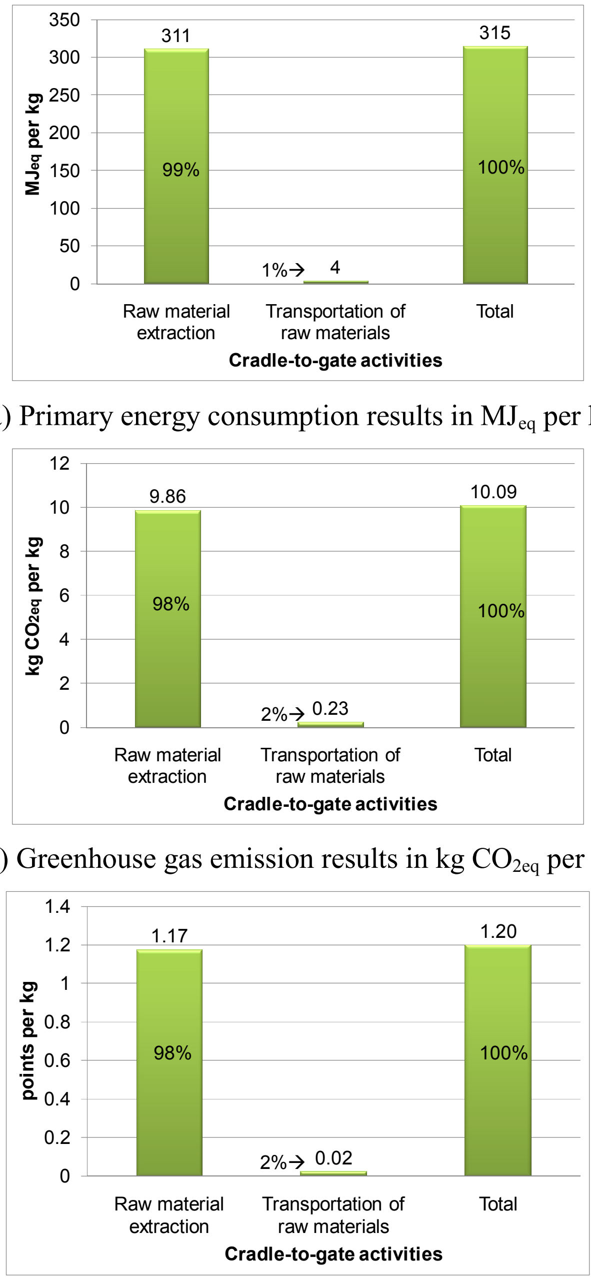
This assessment produced the embodied energy results which are the primary energy consumption and greenhouse gas emissions. The total environmental impacts or a single score results are also given as a full Life Cycle Assessment. These results are expressed in a unit of MJ_{eq} per kg, kg CO_{2eq} per kg and points per kg respectively. The charts in Figure 8.8 display the results in terms of the raw material extraction and the transportation of the raw materials from suppliers to Boeing Research and Technology Australia as depicted in Table 8.4. The last bar of the charts gives the total results of the two main embodied energy sources which are the sum of the raw material extraction and the transportation of the raw materials. The total results of these two embodied energy sources are also provided in the last bar of Figures 8.8 (a) to (c). On the whole, the raw materials for a kilogram of carbon fibre composite provides total embodied energy results of 315 MJ_{eq}, 10 kg CO_{2eq} and 1.2 point.

The raw material extraction constitutes 98% to 99% of these results, whilst 1% to 2% comes from the transportation of the raw materials as labelled in Figure 8.8. The distinct contributions of the two embodied energy sources are clearly revealed. That is, that the embodied energy from the raw material extraction is significantly higher than the embodied energy from the transportation. The finding suggests that the embodied energy of the carbon fibre composite can be reduced in two different directions.

The first direction is to reduce the high embodied energy of the raw material extraction by using alternative raw materials with low embodied energy. The second direction is to be selective in choosing the suppliers in order to ensure low embodied energy in their delivery transportation.

Ideally, the first direction would be the best option as it can reduce the embodied energy dramatically by changing some of the raw materials as the raw material extraction actually contributes a large portion in the total embodied energy result. However, it requires further research and development in finding an alternative or a new raw material which requires further investment of the supporting systems. Therefore, this direction can only be targeted as a long term product development plan.

In practice, the second direction would be more attractive as it is a fast and a simple approach which requires only a careful consideration in selecting the suppliers. For instance, the selected suppliers should supply the raw materials that are manufactured locally or require less energy-intensive transportation system for transporting the raw materials.



(a) Primary energy consumption results in MJ_{eq} per kg

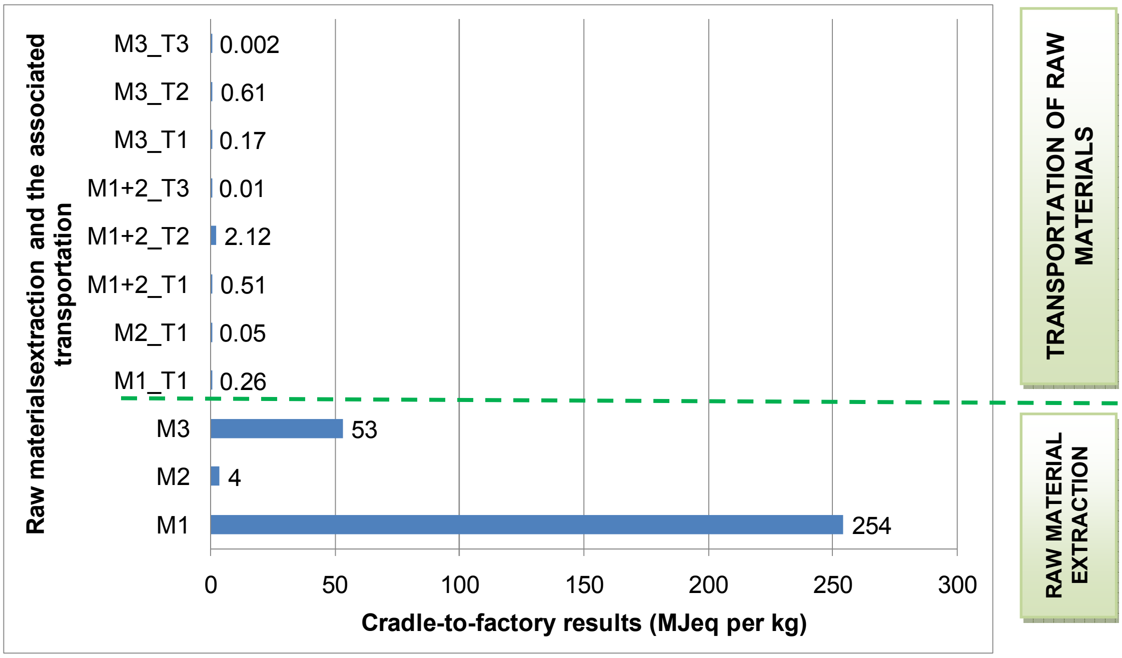
(b) Greenhouse gas emission results in kg CO_{2eq} per kg

(c) Total environmental impacts results in points per kg

Figure 8.8: The cradle-to-factory results for the carbon fibre composite.

To enhance the implementation of these suggestions, Figure 8.9 explicitly presents the embodied energy for each raw material and its corresponding transportation method. These results are produced from the detailed input data such as the MSDs and the actual location of the suppliers for all raw materials provided by Boeing Research and Technology Australia. Raw materials (M1) to (M3) represent different types

Figure 8.9 reveals that the embodied energy of the carbon fibre composite from Boeing Research and Technology Australia was dominated by the combination of several raw materials which originated from overseas suppliers. As a result, a number of hot spots which are the raw materials or the suppliers that have significantly high values are revealed in Figure 8.9.



Note:Raw material types (M), First transportation of the raw material (M_T1), Second transportation of the raw material (M_T2), Third transportation of the raw material (M_T3), Fourth transportation of the raw material (M_T4)

Figure 8.9: The detailed embodied energy results (MJ_{eq} per kg) of the cradle-to-factory analysis which displays types and transportation of raw materials.

In this occasion, the raw material (M1) contributes the most followed by the raw material (M) and (M2) whereby the obvious hot spots of the supplier's transportation are the transportations of the raw materials (M1+2) and (M3). Similarly, these higher contributions of the embodied energy for the transportation methods were observed with notable reasons. Since these raw materials were required in high quantities, they needed to be imported from overseas. Therefore a combination of transportation types was utilised which were the road and water transportation. As shown in Figure 8.9, the transportation of the raw material (M1+M2_T2) and (M3_T2) are relatively high due to the long distance shipping distance from Germany to Melbourne. At the same time, some of the raw materials also needed to be transported on road over a significantly long distance i.e. the transportation of raw material (M1_T1) from Switzerland to Germany and the transportation of raw material (M1+2_T1) from different cities in Germany.

Consequently, these hot spots can be minimised and eliminated by approaching the following recommendations.

- Change the raw material (M1) and (M3) to alternative materials which have lower embodied energy in their raw material extraction.
- Change the suppliers of the raw material (M1) and (M3) to local manufacturers. This is because they came from Europe and also involved in the long distance travel by the road transportation.
- Improve the transportation system by avoiding to use the road transportation for a long distance.
- Change the transportation types by leaning towards the water and rail transportation.

8.5.2 Cradle-to-grave Results and Discussion

As in the cradle-to-grave analysis, the Life Cycle Assessment method was used to assess the embodied energy of the whole life cycle of a carbon fibre and a cold-formed titanium aircraft hinge fittings as shown in Figure 8.10. This assessment produced the two embodied energy results and the full Life Cycle Assessment result. They are the primary energy consumption, greenhouse gas emissions and total environmental impacts or a single score. These results are expressed in a unit of MJ_{eq} per aircraft hinge fitting, kg CO_{2eq} per aircraft hinge fitting and points per aircraft hinge fitting respectively.

In this section, the three results of the two aircraft hinge fittings are presented in the bar charts in Figures 8.11 to 8.13. Each figure provides two bar charts which represent the embodied energy results for with and without the operation process during its life span of 20,000 flights. These charts display the results in terms of the life cycle stages which are the materials, manufacturing process, usage and end-of-life stages as illustrated in Figure 8.10. The last bar of the charts gives the total results of the two aircraft hinge fittings which are the sum of the four life cycle stages. The blue bar presents the cold-formed titanium aircraft hinge fitting and the red bar shows the carbon fibre composite aircraft hinge fitting.

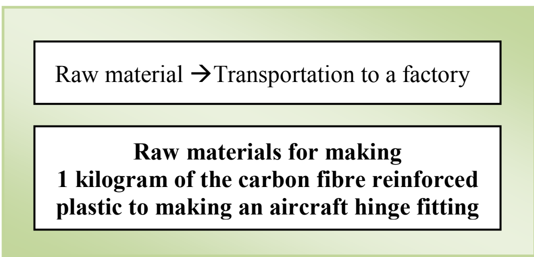
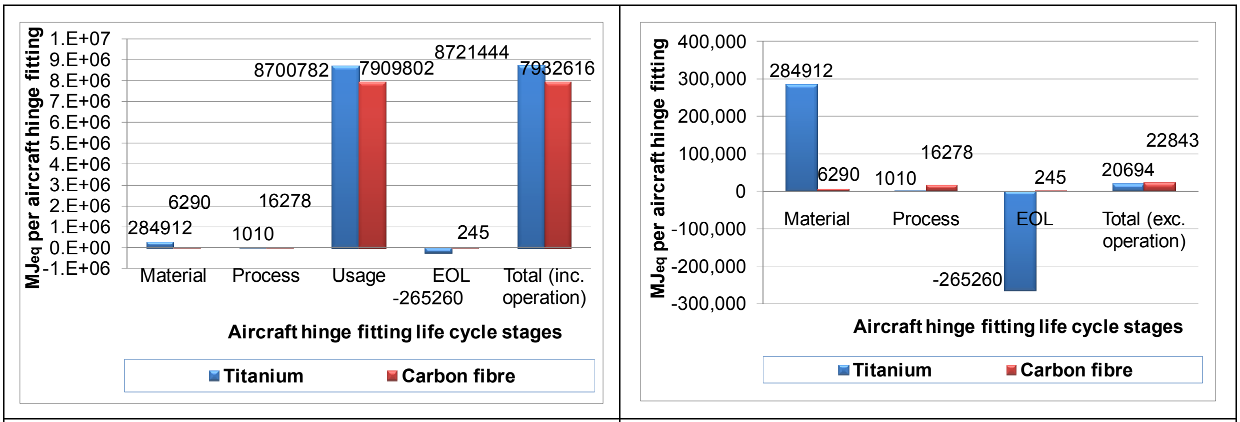


Figure 8.10: Life cycle stages of an aircraft hinge fitting.



(a) (b)

Figure 8.11: Embodied energy of the two aircraft hinge fittings in a unit of MJ_{eq}.

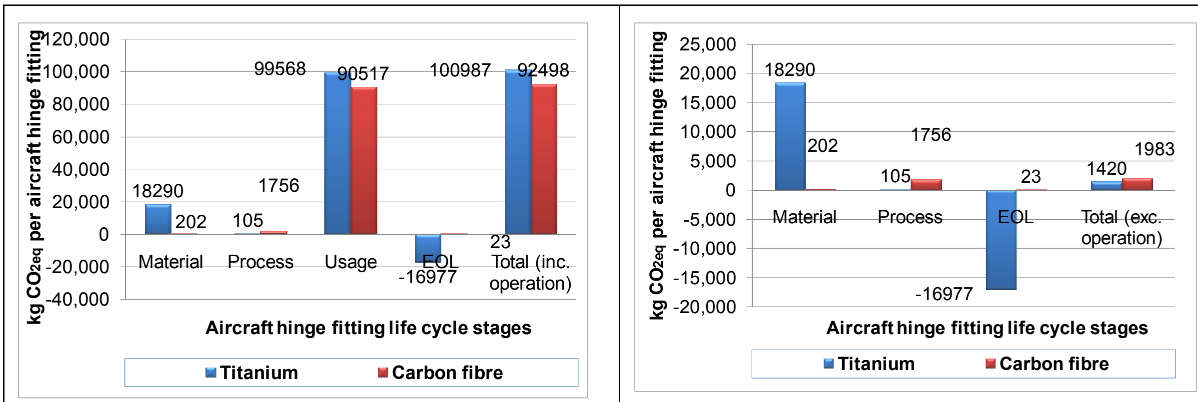
Charts in Figure 8.11 presents the embodied energy results in the primary energy consumption perspective which was assessed by the Cumulative energy demand version 1.04 (CED1.04) method as introduced in Section 8.2.2. Figure 8.11 (b) reveals that the embodied energy of the aircraft hinge fittings at the material life cycle stage are 284,912 MJ_{eq} for the cold-formed titanium aircraft hinge fitting and 7,290 MJ_{eq} for the carbon fibre composite aircraft hinge fitting. This 98% of reduction is due to the fact that titanium requires a relatively high energy during the extraction process.

Another advantage of the carbon fibre composite aircraft hinge fitting is found at the usage stage in Figure 8.11 (a) where 9% of the fuel consumption is saved during the installation and operation activities as this aircraft hinge fitting is lighter than the cold-formed titanium aircraft hinge fitting. Nevertheless, the shortcoming of the carbon fibre composite aircraft hinge fitting is in the manufacturing process where its embodied energy is considerably higher than the cold-formed titanium aircraft hinge fitting by 94%.

However, the end-of-life or the disposal life cycle stage of the cold-formed titanium aircraft hinge fitting performs better than the carbon fibre composite aircraft hinge fitting as can be observed in Figure 8.11 (b). This is because titanium was assumed as 100% recycling, whereas the carbon fibre composite aircraft hinge fitting was assumed as 100% landfill. Therefore, the embodied energy of the cold-formed titanium aircraft hinge fitting at this stage is -265,260 MJ_{eq}. This indicates the gaining energy back from the recycling process by 265,260 MJ_{eq}. The carbon fibre composite aircraft hinge fitting gains an embodied energy of 245 MJ_{eq} from the landfill process.

Overall, the total embodied energy results for the life cycle of the cold-formed titanium aircraft hinge fitting is 8.7 million MJ_{eq} whereby the embodied energy of the carbon fibre composite aircraft hinge fitting is 7.9 million MJ_{eq}. Figure 8.11 (a) shows that the embodied energy of the life cycle of an aircraft hinge fitting can reduce significantly by 9% when it is fabricated from the carbon fibre composite instead of the cold-formed titanium. The dramatic reduction is due to the embodied energy at the material and usage stages of the cold-formed titanium aircraft hinge fitting which are markedly 98% and 9% respectively higher than the carbon fibre composite aircraft hinge fitting.

Figures 8.12 (a) and (b) presents the embodied energy results in the greenhouse gas emission perspective. These results were assessed by the IPCC GWP 100a version 1.00 (IPCC1.00) as presented in Section 8.2.2.



(a) (b)

Figure 8.12 Embodied energy results of the two aircraft hinge fittings in a unit of kg CO_{2eq}.

The embodied energy of the aircraft hinge fittings in Figure 8.12 (b) at the material life cycle stage are 18,290 kg CO_{2eq} for the cold-formed titanium aircraft hinge fitting. Furthermore, 202 kg CO_{2eq} for the carbon fibre composite aircraft hinge fitting. This 99% of reduction is due to the fact that titanium requires relatively high energy during the extraction process, therefore the emissions of the greenhouse gases are subsequently high. Another advantage of the carbon fibre composite aircraft hinge fitting is found at the usage stage in Figure 8.12 (a) where 9% of the greenhouse gas emissions is reduced during the installation activities as the aircraft hinge fitting is lighter than the cold-formed titanium aircraft hinge fitting. Nevertheless, the shortcoming of the carbon fibre composite aircraft hinge fitting is in the manufacturing process where its embodied energy is considerably higher than the cold-formed titanium aircraft hinge fitting by 94%.

However, the end-of-life or the disposal life cycle stage of the cold-formed titanium aircraft hinge fitting performs better than the carbon fibre composite aircraft hinge fitting. This is because titanium was assumed as 100% recycling, whereas the carbon fibre composite aircraft hinge fitting was assumed as 100% landfill. Therefore, the embodied energy of the cold-formed titanium aircraft hinge fitting at this stage is -16,977 kg CO_{2eq}. This indicates the gaining energy back from the recycling process by 16,977 kg CO_{2eq}. The carbon fibre composite aircraft hinge fitting gains an embodied energy of 23 kg CO_{2eq} from the landfill process.

Overall, the total embodied energy results for the life cycle of the cold-formed titanium aircraft hinge fitting is 100,987 kg CO_{2eq} whereby the embodied energy of the carbon fibre composite is 92,498 kg CO_{2eq}. Figure 8.12 (a) shows that the embodied energy of the life cycle of an aircraft hinge fitting can reduce significantly by 8.4% when it is fabricated from the carbon fibre composite instead of the cold-formed titanium. The dramatic reduction is due to the embodied energy at the material and the usage stages of the titanium is markedly 99% and 9% respectively higher than the carbon fibre composite.

Figures 8.13 (a) and (b) presents the total environmental impacts using the Eco-Indicator 99 H/A version 2.03 method as stated in Section 8.2.2. This is a full Life Cycle Assessment analysis which calculates all emissions including airbourne, waterbourne, soil and any wastes into the environmental impacts which have an effect towards human health, the ecosystem quality and resource use impacts.

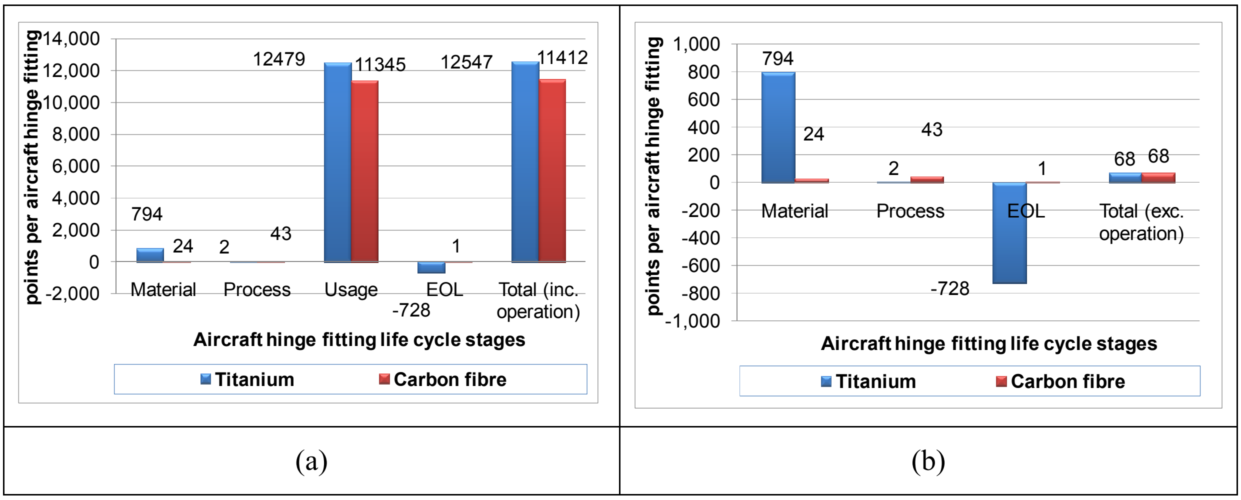


Figure 8.13: Embodied energy results of the two aircraft hinge fittings in a unit of points.

These impacts are then calculated into a single score which is expressed in points unit. The total environmental impact of the aircraft hinge fittings at the material life cycle stage are 794 points for the cold-formed titanium aircraft hinge fitting and 24 points for the carbon fibre composite aircraft hinge fitting. This 97% of reduction as can be seen in Figure 8.13 (b) is due to the fact that titanium requires relatively high energy during the extraction process therefore high emission substances which causes high environmental impacts.

Another advantage of the carbon fibre composite aircraft hinge fitting is found at the usage stage in Figure 8.13 (a) where 9% of the environmental impacts is reduced during the installation and operation activities as the aircraft hinge fitting is lighter than the cold-formed titanium aircraft hinge fitting. Nevertheless, the shortcoming of the carbon fibre aircraft hinge fitting is in the manufacturing process as shown in Figure 8.13 (b) where its embodied energy is considerably higher than the cold-formed titanium aircraft hinge fitting by 95%.

However, the end-of-life or the disposal life cycle stage of the cold-formed titanium aircraft hinge fitting performs better than the carbon fibre aircraft hinge fitting. This is because titanium was assumed as 100% recycling, whereas the carbon fibre aircraft hinge fitting was assumed as 100% landfill. Therefore, the total environmental impact of the cold-formed titanium aircraft hinge fitting at this stage is -728 points. This indicates the gaining energy back from the recycling process by 728 points. The carbon fibre aircraft hinge fitting gains the total environmental impact of 1 point from the landfill process.

Overall, the total environmental impact results for the life cycle of the cold-formed titanium aircraft hinge fitting is 12,547 points whereby the embodied energy of the carbon fibre aircraft hinge fitting is 11,412 points. Figures 8.13 (a) and (b) show that the embodied energy of the life cycle of an aircraft hinge fitting can reduce significantly by 9% when it is fabricated from the carbon fibre composite instead of the cold-formed titanium. The dramatic reduction is due to the embodied energy at the material and usage stages of the titanium aircraft hinge fitting are markedly 97% and 9% respectively higher than the carbon fibre composite aircraft hinge fitting.

According to the results in Figures 8.11 to 8.13, a carbon fibre composite aircraft hinge fitting has a significant lower environmental impacts than a cold-formed titanium aircraft hinge fitting. The gained benefits making an aircraft hinge fitting out of the carbon fibre reinforced plastic rather than the cold-formed titanium are ascribed in the three results as follows.

First of all, in terms of the energy consumption, an aircraft hinge fitting that is made from the carbon fibre composite can saved the energy consumption during its life cycle up to 9%. Secondly, in the perspective of the greenhouse gas emissions, an aircraft hinge fitting that is made from the carbon fibre composite can reduce the amount of greenhouse gases that are incurred during its life cycle by 8%. Lastly, the total environmental impacts that can effect human health, the ecosystem quality and resource use are reduced significantly by 9%.

On the whole, these benefits are mainly gain during the material and the usage stages of the aircraft hinge fitting life cycle. This is because the carbon fibre reinforced plastic uses significantly less extraction energy and fuel consumption than the cold-formed titanium. However, the carbon fibre aircraft hinge fitting has a higher embodied energy and environmental impacts than the cold-formed titanium aircraft hinge fitting at the manufacturing process stage and the landfill process of the end-of-life stage.

8.6 Conclusion

This chapter presented the cradle-to-factory and the cradle-to-grave analyses which assessed the embodied energy analysis of the raw materials of the carbon fibre and the aircraft hinge fittings that are made from the carbon fibre reinforced plastic and cold-formed titanium.

The methodology overview was presented by defining the scopes and assumptions of the input data which is required for the calculation of the embodied energy analysis. The Life Cycle Assessment method was selected to calculate the embodied energy of the raw materials and the two different aircraft hinge fittings. This assessment produced the two embodied energy results and the full Life Cycle Assessment result. They were the primary energy consumption, the greenhouse gas emissions and the total environmental impacts or a single score.

These results were expressed in a unit of MJ_{eq}, kg CO_{2eq} and points respectively. The MJ_{eq} and kg CO_{2eq} results were the generic embodied energy values, however these two units are only considered the primary energy consumptions and the greenhouse gas emissions. Therefore, the points results were generated from the full Life Cycle Assessment which covers all emission substances that can affect the environment in terms of human health, ecosystem and resource (fossil fuels and mineral) use.

Thereafter, the description of the raw materials and the two different aircraft hinge fittings was specified. Consequently, the input data of the cradle-to-factory and the cradle-to-grave analyses was determined on the basis of the scopes, assumptions and descriptions.

The results of the cradle-to-factory analysis demonstrated that the raw materials of a kilogram of carbon fibre reinforced plastic consumes 315 MJ_{eq}, emits 10 kg CO_{2eq} and has the total environmental impact of 1.2 point as shown in Figure 8.8. The results are contributed by 98 to 99% from the raw material extraction and 1% to 2% from the transportation of the raw materials. The suggestions for reducing the embodied energy of the carbon fibre reinforced plastic were given in two different directions. They were using low embodied energy raw material and choosing the suppliers that have low embodied energy in their delivery transportation.

Subsequently, a hot spots analysis was performed to identify the raw materials or the suppliers that have significantly high embodied energy. Whilst, the embodied energy of the raw materials (M1) and (M3) are significantly higher than other raw materials, the transportation of the raw materials (M1+2) and (M3) are also substantially high. Some recommendations were given such as change to local manufacturers and avoiding to use the road transportation by leaning towards the water and rail transportation.

The embodied energy results for the whole life cycle of a carbon fibre aircraft hinge fitting and a cold-formed titanium aircraft hinge fitting were assessed from the cradle-to-grave analysis as shown in

Figures 8.11 to 8.13. These results illustrated that the embodied energy of the carbon fibre aircraft hinge fitting is significantly lower than the cold-formed titanium aircraft hinge fitting. This is owing to the significant reduction of the raw material extraction during its material stage.

Moreover, the carbon fibre aircraft hinge fitting is lighter than the cold-formed titanium aircraft hinge fitting, therefore, the fuel consumption is reduced proportionally during the installation transportation and the operation of the usage stage. These advantages largely outweigh the disadvantages which came from the higher embodied energy during its manufacturing process stage and the landfill process during the end-of-life stage. To sum up, the total embodied energy results of the two aircraft hinge fittings life cycle revealed that:

- An aircraft hinge fitting that is made from the carbon fibre reinforced plastic uses 9% less energy consumption during its life cycle.
- An aircraft hinge fitting that is made from the carbon fibre reinforced plastic emits 8% less amount of greenhouse gases that are incurred during its life cycle.
- An aircraft hinge fitting that is made from the carbon fibre reinforced plastic causes 9% less environmental impacts that can effect human health, the ecosystem quality and resource use during its life cycle.

CHAPTER 9

CONCLUSION

The Composites: Calculating their embodied energy study was a collaboration between the Queensland Government - Department of Employment, Economic Development and Innovation (DEEDI), seven composite product manufacturers, R&D, education and training, materials suppliers and the Life Cycle Engineering & Management (LCEM) Research Group @ the University of New South Wales. The project aimed at studying the embodied energy for the Cradle-to-factory and the entire life cycle of the composite materials and products.

The expected outcome of the project was the material and energy flow of the six participant companies for the cradle-to-factory analysis. Subsequently, the environmental impacts of the model were analysed to produce the results in terms of MJ_{eq} per kg, kg CO_{2eq} per kg and points per kg. Consequently, thirteen case studies were further analysed for the cradle–to-grave analysis which are expressed in the unit of the MJ_{eq}, kg CO_{2eq} and single score points. The analysis from these case studies were used to compare the whole life cycle analysis of the composite products with similar products produced from the conventional materials for different applications. Therefore, the material life cycle stage was calculated based on the 1 kilogram of the cradle-to-factory results which were multiplied with the total weight of the product, down to the manufacturing process into a product which would then be installed, maintained and disposed.

This report firstly presented the system description and the assumption of the cradle-to-factory and the cradle–to-grave analyses. Secondly, the methodology of the embodied energy analysis elucidated on the basis of the methodology overview, data collection approach and the material and energy flow model. The Life Cycle Assessment analysis was employed to assess the embodied energy of the cradle-to-factory and the cradle–to-grave analyses for the six companies. The Cumulative Energy Demand version 1.04 (CED 1.04), the IPCC 2007 GWP 100a version 1.00 (IPCC 1.00) and the Eco-Indicator 99 H/A version 2.03 (EI99 2.03) methods were the assessment tool from the LCA software, SimaPro 7.1.8[6]. Subsequently, the Life Cycle Assessment results were used to illustrate the cradle-to-factory analysis for the six composite materials and the cradle-to-grave analysis for thirteen case studies. Moreover, the results of the embodied energy analyses in terms of conventional air pollutants are provided in Appendix A. In addition to this, a spreadsheet model was also developed for future applications and the technical manual of the

[6] PRe consultants BV, "SimaPro," 7 ed. The Netherlands, 2006.

material and energy flow spreadsheet model and the database background for the embodied energy analysis are included in the last section of the appendices.

On the whole, the cradle-to-factory results of this project suggested that:

- The embodied energy of the cradle-to-factory analysis for the six composite materials in this project is comprised of the extraction energy process and the transportation from suppliers to the manufacturers. The cradle-to-factory results reveal that the predominant contributor to the embodied energy of the fibre composites came from the energy required during the extraction process.
- The extraction energy of the raw materials for the composite materials is influenced mainly by the quantities and the types of resins used. In this case, it is based on the databases from the Life Cycle Assessment software, where 1 kilogram of fibreglass has lower extraction energy than 1 kilogram of resin, whilst 1 kilogram of carbon fibre has the highest extraction energy.
- The higher contributions of the transportation were caused by a number of factors. Road transportation was found to be the main contributing factor as it utilised higher amounts of non-renewable fossil fuel such as crude oil to transport the raw material freight over a long distance. Shipment of raw materials from overseas can also increase the embodied energy of the composite materials. Interestingly, it was found that the accumulation of the shipment of several raw materials from various overseas suppliers can further increase the embodied energy of the transportation. For instance, suppliers that were found in this study came from various locations in the Asia, Europe and US regions.

The cradle-to-grave results of this project suggested that:

- *Material stage:* Composite products have significantly lower embodied energy during their material stage the traditional product. This is large due to the traditional materials require a relatively high amount of energy during their extraction process.
- *Manufacturing process (process):* Most of the composite products have higher embodied energy than the traditional products during the manufacturing process stage.
- *Usage stage:* Composite products perform considerably better than the traditional products at this stage due to their light-weight and corrosive resistance properties which save the fuel consumption.

- *End-of-Life stage:* Despite many advantages, composite products have the shortcoming at the end-of-life stage where the composite products are currently 100% landfill but the traditional product such as steel and aluminium is 65 to 70% recyclable.

Ultimately on the basis of the scopes and assumptions of this analysis, it was found that composite products are estimated to perform better than the traditional products in terms of their embodied energy that incurred during their life cycle stages. At the material stage, they perform the best. Their outstanding natures such as the strength and lightness are genuinely an advance on the traditional materials in this modern era.

CHAPTER 10
RECOMMENDATIONS

The following recommendations are summarised as generic suggestions for future projects and composite product development. The suggestions are based on the results obtained from the methodology and embodied energy results acquired from the cradle-to-factory and the cradle-to-grave analyses of the composite products.

Recommendations for the embodied energy results:

- For this project a hot spot was defined as the raw materials and/or suppliers which have a high contribution to the embodied energy results of the composite products. The hot spots analysis was conducted in order to make further suggestions in order to minimise or eliminate the identified raw materials and/or suppliers. As a result, the raw materials and suppliers which predominantly contributed to the cradle-to-factory were identified. Therefore, the suggestions to reduce these hot spots were made such as avoiding the utilisation of the road transportation for a long distance and also encouraging the manufacturers to use rail and/or water transportation. Moreover, selecting local suppliers was also suggested rather than those from overseas.
- The shortcoming of the disposal process of the composite products was found when their embodied energy results were compared with the traditional products which have a higher recycling rate such as 70% for steel and 65% aluminium as suggested by the Australian household waste scenarios. Therefore, further challenge is to improve the recyclability of the composite products. This is not only for improving the embodied energy efficiency but also to improving the competitiveness in the international market where the recycling rate is one of the main requirements for the exporting products into countries such as Europe commission and Japan.

Recommendations for the future project:

- The detailed input data should be investigated further in order to increase the accuracy of the cradle-to-factory and the cradle-to-grave analyses. For instance, some of the raw materials and suppliers were excluded from the cradle-to-factory analysis due to the limited data available from the participant companies.
- With limited resources, more participants should be involved in the project to provide input data for more case studies or to support the detailed information for such areas as extended suppliers. This will enhance the cradle-to-factory analysis where all the transportation systems are included such as those used overseas.
- For future work, the optimisation can be further analysed to improve the hot spots as found in the cradle-to-factory results. A hot spot is defined as the raw materials and/or suppliers which have a high contribution to the embodied energy results. Therefore, the identified raw materials and/or suppliers can be minimised or eliminated using sensitivity analysis to test the implementation in a practical environment.
- The energy efficiency during the manufacturing, installation, usage and maintenance processes can be investigated further to improve their environmental performance. This can be achieved by measuring or monitoring the energy consumption during the operation of these activities. Subsequently, the Life Cycle Assessment can be performed and attempted to improve its performance.
- This investigation should be accompanied by a Life Cycle Costing analysis in order to understand the true cost of fibre composite products in a cradle-to-grave scenario. This is needed in order to completely assess the sustainability of the product, which will lead to a win-win situation where the environment is protected and the economy sustained.

- mposite products have the shortcoming at the end-of-life stage where the composite products are currently 100% landfill but the traditional product such as steel and aluminium is 65 to 70% recyclable.

Ultimately on the basis of the scopes and assumptions of this analysis, it was found that composite products are estimated to perform better than the traditional products in terms of their embodied energy that incurred during their life cycle stages. At the material stage, they perform the best. Their outstanding natures such as the strength and lightness are genuinely an advance on the traditional materials in this modern era.

ACKNOWLEDGEMENTS

This project was funded by the Department of Employment, Economic Development and Innovation (DEEDI), the State of Queensland. The embodied energy analysis was conducted by the Life Cycle Engineering & Management Research Group @ the University of New South Wales (LCEM).

The following steering committee and individuals have assisted in providing input data for the analysis as well as participating in and facilitating the project:

Jason Manttan (DEEDI)

Thomas Wechselberger (DEEDI)

Trevor Panozza (Ampelite Fibreglass Pty Ltd)

Ram Srivatsa (Ampelite Fibreglass Pty Ltd)

Andrew Glynn (Boeing Research & Technology Australia)

Christopher Howe (Boeing Research & Technology Australia)

Jason Perkins (B-Pods Pty Ltd (Tractile))

Jovana Dukic (B-Pods Pty Ltd (Tractile))

Frank Rosselli (Exel Composites)

Chris Heaton (Mustang Marine Australia Pty Ltd)

Michael Kemp (Wagners Composite Fibre Technologies Manufacturing Pty Ltd)

Noel Larkin (Wagners Composite Fibre Technologies Manufacturing Pty Ltd)

Associate Professor Thiru Aravinthan (Centre of Excellence in Engineered Fibre Composites)

Bob Paton (Manufacturing Skills Australia)

Jamie Groth (Nupol Composites)

Mathew Horman (Nupol Composites)

Genelle Coghlan (Colan Australia)

Toho-Tenex

APPENDIX A

TABLES OF AIR POLLUTANTS RESULTS

Cradle-to-grave results for a square metre of Tractile roof tile

(B-Pods Pty Ltd)

Cradle-to-grave	Materials/Processes description	Unit	Amount per 1 m2 roofing	Primary energy consumption (MJeq)	Greenhouse gas emissions (kg CO2eq)	Total environmental impact (points)	CO (kg)	CO2 (kg)	NO2 (kg)	SO2 (kg)	Partibulate (unspecified) kg	VOC (kg)
Material & Process	10 kg of C1 material	kg	10	114.37	10.96	0.47	2.55E-03	10.91	1.68E-02	6.79E-04	3.95E-03	3.44E-04
Process	Electricity consumption	kwh	4.0323	155.65	14.96	0.59	3.98E-03	14.82	1.68E-02	3.51E-03	5.05E-03	3.44E-04
Installation	Steel battens	kg	2.75	84.67	6.78	0.69	2.05E-01	6.51	7.54E-05	1.18E-02	1.30E-01	3.42E-06
	Steel screws production	kg	0.06	1.85	0.15	0.02	4.46E-03	0.14	1.64E-06	2.57E-04	2.83E-03	7.46E-08
	Cutting roof sheet	kWh	0.02	0.21	2.04E-02	7.64E-04	9.11E-06	1.99E-02	-5.26E-21	6.12E-05	5.96E-06	6.52E-12
	Cutting steel battens	kWh	0.02	0.21	2.04E-02	7.64E-04	9.11E-06	1.99E-02	-5.26E-21	6.12E-05	5.96E-06	6.52E-12
	Drilling & screwing; Cordless drill	kWh	5.830E-03	0.06	5.94E-03	2.23E-04	2.66E-06	5.80E-03	-1.53E-21	1.78E-05	1.74E-06	1.90E-12
	Transportation for installation:13.01kg*0.001t/kg*200km	tkm	2.562	6.17	3.80E-01	1.85E-02	1.48E-03	3.70E-01	-6.54E-19	2.89E-04	2.20E-04	7.57E-13
Maintenance	Warranty 30 years	kWh	0	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EOL	Transportation for EOL	tkm	2.562	6.17	0.38	1.85E-02	1.48E-03	0.37	-6.54E-19	2.89E-04	2.20E-04	7.57E-13
	EOL option	%	100	-20.01	2.75	-0.06	-0.12	-0.35	-4.11E-18	-4.72E-03	-1.45E-04	-1.26E-06
Total	1m2 of Tractile roof tile	m2	1.000	390.621	40.411	1.863	0.095	36.730	0.034	0.015	0.143	0.001

Cradle-to-grave results for a square metre of Wonderglas sheeting

(Ampelite Fibreglass Pty Ltd)

Cradle-to-grave	Materials/Processes description	Unit	Input: Amount per 1 m2 roofing	Primary energy consumption (MJeq)	Greenhouse gas emissions (kg CO2eq)	Total environmental impact (points)	CO (kg)	CO2 (kg)	NO2 (kg)	SO2 (kg)	Partibulate (unspecified) kg	VOC (kg)
Material	Wonderglas GC : Option 2	kg	2.4	2.91E+01	1.43E+00	1.18E-01	3.03E-03	1.17E+00	4.04E-05	1.44E-03	1.08E-03	3.47E-05
Process	Total ellectricity consumption	kWh	0.81504	9.70E+00	1.08E+00	2.45E-02	4.14E-04	1.07E+00	#######	2.94E-06	2.05E-04	2.69E-10
Installation	Assumed the weight of steel battens based	kg	0.71	1.90E+01	1.50E+00	1.69E-01	5.44E-02	1.44E+00	#######	2.23E-03	3.43E-02	4.65E-07
	Galvanisation process for steel batten	m2	0.159	1.21E+01	1.12E+00	6.12E-02	2.47E-03	1.08E+00	3.01E-04	6.78E-03	1.52E-04	2.08E-10
	Assumed the weight screws based on the s	kg	0.39	1.20E+01	1.15E+00	4.58E-02	4.28E-04	1.12E+00	#######	7.92E-04	2.99E-03	3.74E-10
	Cutting roof sheet	kWh	0.02	2.09E-01	2.04E-02	7.64E-04	9.11E-06	1.99E-02	#######	6.12E-05	5.96E-06	6.52E-12
	Cutting steel battens	kWh	0.005163	5.40E-02	5.26E-03	1.97E-04	2.35E-06	5.14E-03	#######	1.58E-05	1.54E-06	1.68E-12
	Drilling & screwing; Cordless drill	kWh	0.011667	1.22E-02	1.19E-03	4.46E-05	5.32E-07	1.16E-03	#######	3.57E-06	3.48E-07	3.80E-13
	Transportation for installation:13.01kg*0.00	tkm	0.7	1.69E+00	1.04E-01	5.06E-03	4.04E-04	1.01E-01	#######	7.90E-05	6.02E-05	2.07E-13
EOL	Transportation for EOL	tkm	0.7	1.69E+00	1.04E-01	5.06E-03	4.04E-04	1.01E-01	#######	7.90E-05	6.02E-05	2.07E-13
	EOL option	%	100	-6.06E+00	-7.03E-02	-1.94E-02	#######	#######	#######	#######	-1.76E-05	#######
Total CTG	Wonderglas GC roof sheeting: option 2	m2	1	8.91E+01	7.52E+00	4.35E-01	2.94E-02	7.08E+00	3.41E-04	1.03E-02	3.90E-02	3.48E-05

Cradle-to-grave results for Mustang 430 powerboat hull

(Mustang Marine Australia Pty Ltd)

Cradle-to-grave	Materials/Processes description	Unit	Input: Amount per powerboat hull	Primary energy consumption (MJeq)	Greenhouse gas emissions (kg CO2eq)	Total environmental impact (points)	CO (kg)	CO2 (kg)	NO2 (kg)	SO2 (kg)	Partibulate (unspecified) kg	VOC (kg)
Material	Mustang 430 hull	hull	1	97370.79	3009.28	504.01	5.72	2972.31	2.97E-01	6.99E-01	3.87E+00	3.09E-02
	Polyurethane foam	kg	45	3821.13	245.26	20.76	0.15	220.54	7.97E-05	1.14E-01	3.71E-04	3.97E-04
	Plywood	kg	170	2339.43	206.08	24.26	2.14	24.32	5.60E-08	8.14E-01	5.62E-03	1.68E-01
	Transportation for plywood	tkm	33.165	79.85	4.91	0.24	0.02	4.70	1.34E-20	3.75E-03	5.54E-07	9.79E-12
	Transportation for foam	tkm	13.804	33.24	2.04	0.10	0.01	1.95	5.59E-21	1.56E-03	2.31E-07	4.08E-12
Process	Total energy consumption p	kWh	1567	15411.74	1499.80	56.25	0.67	16.66	-2.23E-17	4.50E+00	2.87E-02	4.80E-07
Installation	Transportatioin for distributio	km	200	2447.68	142.02	8.46	3.21	136.62	-5.94E-18	1.33E-01	9.56E-02	2.91E-10
Maintenance	No resurfacing required	kwh	0	0.00	0.00	0.00	0.00	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
End-of-life	Transportatioin for landfill is	km	200	2447.68	142.02	8.46	3.21	136.62	-5.94E-18	1.33E-01	9.56E-02	2.91E-10
	EOL option	%	100	654.53	324.28	2.22	0.49	22.73	-2.41E-15	-3.31E-03	-6.36E-03	3.67E-08
Total CTG	Mustang 430 powerboat hul	hull	1	124606.08	5575.69	624.75	15.61	3536.45	0.30	6.40	4.09	0.20

Cradle-to-grave results for a linear metre of Exel I-Beam

(Exel Composites)

Cradle-to-grave	Materials/Processes description	Unit	Input: Amount per 1 m	Primary energy consumption (MJeq)	Greenhouse gas emissions (kg CO2eq)	Total environmental impact (points)	CO (kg)	CO2 (kg)	NO2 (kg)	SO2 (kg)	Partibulate (unspecified) kg	VOC (kg)
Material	1m of C4 material for I beam	m	1	8.498E+01	4.025E+00	4.397E-01	6.50E-03	3.95E+00	3.18E-02	7.75E-04	3.90E-03	7.97E-05
Process	Total ellectricity consumption	kWh	1.101	1.311E+01	1.453E+00	3.305E-02	5.59E-04	1.44E+00	1.66E-03	3.98E-06	2.77E-04	3.64E-10
Installation	Transportation for distribution: 3.28	tkm	0.6562	1.580E+00	9.721E-02	4.741E-03	3.78E-04	9.48E-02	4.18E-04	7.41E-05	5.64E-05	1.94E-13
EOL	Transportation for EOL	tkm	0.6562	1.580E+00	9.721E-02	4.741E-03	3.78E-04	9.48E-02	4.18E-04	7.41E-05	5.64E-05	1.94E-13
	Transportation for landfill: 3.281kg*	%	100	6.035E-01	2.996E-01	2.046E-03	4.55E-04	2.09E-02	2.46E-04	-3.18E-06	-5.88E-06	3.39E-11
Total CTG	A linear metre of Exel I-Beam	m	1	101.85	5.97	0.48	8.27E-03	5.61E+00	3.45E-02	9.24E-04	4.28E-03	7.97E-05

Cradle-to-grave results for a 2.5 linear metre of Wagners power-pole cross-arm

(Wagners Composite Fibre Technologies Manufacturing Pty Ltd)

Cradle-to-grave	Materials/Processes description	Unit	Input: Amount per 1 power-pole cross-arm	Primary energy consumption (MJeq)	Greenhouse gas emissions (kg CO2eq)	Total environmental impact (points)	CO (kg)	CO2 (kg)	NO2 (kg)	SO2 (kg)	Partibulate (unspecified) kg	VOC (kg)
Material	2.5m of C5 material for crossar	kg	9.5	135.47	5.41	0.75	0.003	5.369	4.63E-04	5.42E-04	6.39E-03	1.11E-12
Process	Total ellectricity consumption	kWh	28	275.39	26.80	1.01	0.012	26.193	-1.42E-18	8.05E-02	7.84E-03	8.58E-09
Installation	connection	kg	5	226.37	19.58	1.46	0.386	18.940	-2.09E-18	2.21E-02	2.44E-01	3.27E-06
	Transportation for installation	tkm	2.9	6.98	0.430	0.021	0.002	0.419	1.26E-18	3.27E-04	2.49E-04	8.56E-13
End-of-life	Transportation for disposal site	tkm	2.9	6.98	0.430	0.021	0.002	0.419	1.26E-18	3.27E-04	2.49E-04	8.56E-13
	EOL option	%	100	-43.71	-0.96	-0.14	-0.230	-0.795	-5.76E-18	-8.07E-03	-1.15E-04	-2.24E-06
Total CTG	2.5m power-pole crossarm for 4	m	2.5	607.47	51.69	3.12	0.174	50.545	4.63E-04	9.57E-02	2.58E-01	1.04E-06

Cradle-to-grave results for Boeing's carbon fibre aircraft hinge fitting

(Boeing Research & Technology Australia)

Cradle-to-grave	Materials/Processes description	Unit	Input: Amount per hinge fitting	Primary energy consumption (MJeq)	Greenhouse gas emissions (kg CO2eq)	Total environmental impact (points)	CO (kg)	CO2 (kg)	NO2 (kg)	SO2 (kg)	Partibulate (unspecified) kg	VOC (kg)
Material	20 kg of carbon fibre	hinge fitting	1	6290	202	24	7.74E-01	1.90E+02	5.18E-02	4.37E-02	2.97E-02	6.72E-12
Process	Total ellectricity consu	kWh	1286.6	16278	1756	43	1.26E+00	1.73E+03	1.19E-16	2.92E-02	5.80E-01	4.25E-07
Installation	Installation:(20kg/100	tkm	0.508	29	2	1.02E-01	3.85E-02	1.64E+00	6.44E-19	1.59E-03	1.15E-03	3.49E-12
Usage	Fuel consumption dur	kg	112513.9	7909773	90515	11345	3.03E-01	1.29E+01	5.07E-18	1.25E-02	9.04E-03	2.75E-11
End-of-life	Transportation for EO	tkm	4	231	13	7.99E-01	1.37E-02	3.17E-01	-8.44E-19	-5.34E-04	-2.40E-04	1.14E-09
	EOL option	%	100	14	10	4.94E-02	89	83369	-1.85E-13	185	19	1.04E-06
Total	CTG for 1 carbon fibre	hinge fitting	1	7932616	92498	11412	92	85302	5.18E-02	185	19	1.46E-06

APPENDIX B
TECHNICAL MANUAL: MATERIAL AND ENERGY FLOW SPREADSHEET MODEL

Introduction

The input-output model of the materials and energy flows are prepared in a spreadsheet model using Microsoft Excel. This file contains several worksheets as shown in Figure B.1. The first work sheet is the 'MODEL' worksheet which is used as the interface with the user. It includes the model, sections for data entry, table of the report and a bar chart. Therefore, the data entry can be described as follows.

Figure B.1: Worksheets included in the spreadsheet model.

Model worksheet

Cradle-to-factory analysis of the raw materials and the associated transportation:

1. Enter or alter the input data of raw materials in kilogram in the coloured cell that has an arrow indicated as shown in 'A' of Figure B.1.

2. Enter or alter the input data for the distance of the transportation type for the associated raw materials from suppliers to the manufacturer at the blue text cell which has an arrow sign as shown in 'B' of Figure B.1.

3. The two embodied energy results as shown in C are presented as the primary energy consumption (MJ_{eq}) and the greenhouse gas emissions (kg CO_{2eq}) results which will be generated instantly when you enter the input data above. They are presented in the cells below the input data. These two values are calculated based on the Cumulative Energy Demand (CED) and the IPCC GWP (IPCC) methods.

4. Additional results of the full Life Cycle Assessment from the Eco-Indicator 99 H/A (EI99) method are also given in the third cell below the IPCC results as shown in Figure B.1 from the CED results.

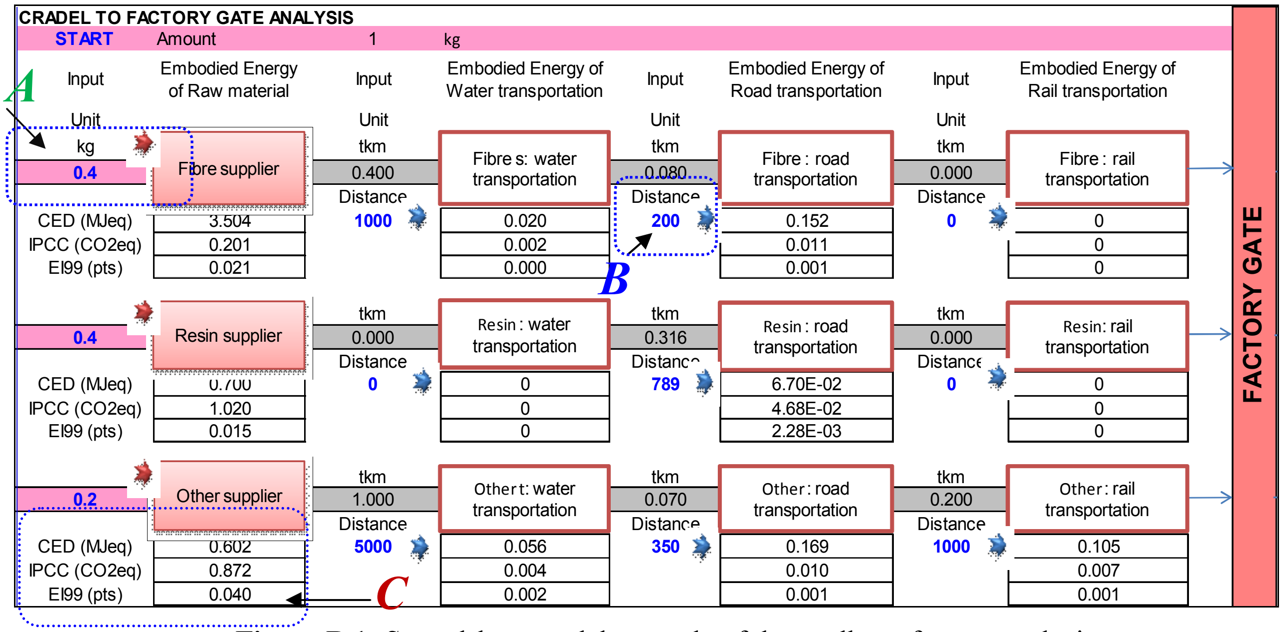


Figure B.1: Spreadsheet model example of the cradle-to-factory analysis.

Cradle-to-grave analysis of the life cycle of a product:

1. The input data for the manufacturing process, the transportation for the installation of the finished product, the maintenance and the disposal process can be entered similarly.
2. The electricity consumption in kWh can be enter in the cell which has an arrow sign as shown in Figure B.2. The results are given in MJ_{eq}, kg CO_{2eq} and points

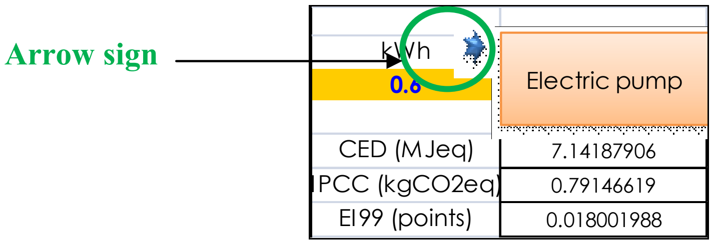


Figure B.2: Electricity consumption entry and the produced results of the cradle-to-grave analysis.

3. The input data for the usage stage was prepared on a basis of the product's analysis scope and assumption. Most of the models would provide certain maintenance and operation process such as energy consumption and transportation involved. The input data can be entered similarly to Figure B.3 entering the value in the cell which has the arrow sign.

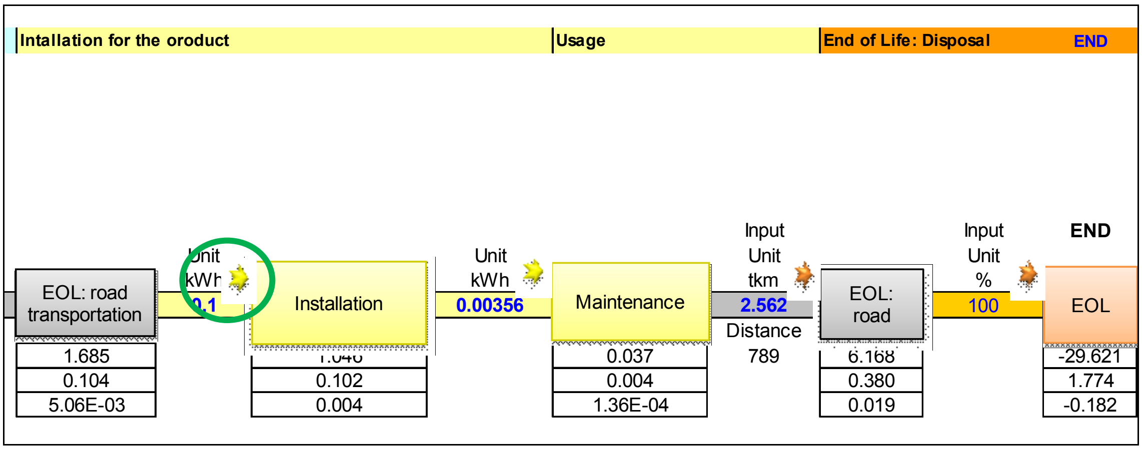


Figure B.3: Spreadsheet model example of the cradle-to-grave analysis.

The presentation of the results in a report format:

The based line model is shown in the table which has blue cells. The results of the analysis are presented in the white table on the right hand side as shown in Figure B.4. This table shows the three results for each of the parameters such as the individual raw materials, all the transportation and electricity until the end-of life of the product.

The results are also provided in bar charts as shown in Figure B.5.

Cradle to factory gate	Table of the input data from the model	Report: Results from the input data from the model			Report: Product life cycle stages result			Report: Results from the input data from the model					
	Input: Amount per 1 kg of composites material	CED 1.04 (MJeq)	IPCC 1.00 (kg of CO2eq)	EI99 2.03 (points)	CED 1.04 (MJeq)	IPCC 1.00 (kg of CO2eq)	EI99 2.03 (points)	CO (kg)	CO2 (kg)	NO2 (kg)	SO2 (kg)	Partibulate (unspecified) kg	VOC (kg)
Extraction energy	0.4	3.504E+00	2.010E-01	2.100E-02	4.806E+00	2.093E+00	7.600E-02	4.027E-01	6.950E-05	1.598E-03	1.869E-03	3.205E-04	0.000E+00
	0.4	7.000E-01	1.020E+00	1.500E-02				1.320E+00	2.156E-04	2.444E-03	5.462E-03	1.771E-03	0.000E+00
	0.2	6.020E-01	8.720E-01	4.000E-02				9.495E-01	2.430E-04	1.430E-03	3.544E-03	1.046E-03	6.873E-04
Transportation: Suppliers to Company	0.400	2.000E-02	2.000E-03	2.399E-04	1.803E-01	1.352E-02	7.898E-04	2.063E-03	2.667E-06	-2.271E-21	2.372E-06	2.422E-10	4.282E-15
	0.08	1.520E-01	1.100E-02	5.000E-04				1.133E-02	4.598E-05	2.568E-21	9.034E-06	1.336E-09	2.362E-14
	0.078	7.305E-03	4.605E-04	4.699E-05				4.042E-04	5.224E-07	-4.577E-22	4.647E-07	4.744E-11	8.389E-16
	0.0004	9.631E-04	5.925E-05	2.890E-06				5.664E-05	2.299E-07	1.284E-23	4.517E-08	6.679E-12	1.181E-16
Total CTF	1	4.986E+00	2.107E+00	7.679E-02	4.986E+00	2.107E+00	7.679E-02	2.686E+00	5.775E-04	5.473E-03	1.089E-02	3.137E-03	6.873E-04
Material	3.5	4.986E+01	2.107E+01	7.679E-01	4.986E+01	2.107E+01	7.679E-01	3.815E+00	7.216E-04	9.151E-03	1.610E-02	4.433E-03	1.203E-04
Process	0.0006	6.141E-03	5.949E-04	1.799E-05	7.165E-03	6.940E-04	2.098E-05	2.129E-07	6.820E-06	-3.455E-23	4.213E-07	1.131E-08	2.001E-13
	0.0001	1.024E-03	9.914E-05	2.998E-06				3.548E-08	1.137E-06	-5.758E-24	7.021E-08	1.886E-09	3.335E-14
Usage	2.75	7.345E+01	5.823E+00	6.549E-01	7.616E+01	6.058E+00	6.724E-01	2.106E-01	4.634E+00	6.579E-18	8.650E-03	1.314E-01	1.799E-06
	0.06	2.716E+00	2.349E-01	1.755E-02				4.632E-03	1.024E-01	2.658E-19	2.651E-04	2.868E-03	3.929E-08
EOL	2.562	6.168E+00	3.795E-01	1.851E-02	-2.345E+01	2.154E+00	-1.636E-01	1.472E-03	3.628E-01	-9.229E-19	2.893E-04	1.088E-10	7.566E-13
	100	-2.962E+01	1.774E+00	-1.821E-01				-1.225E-01	-1.030E+00	-1.445E-15	-4.891E-03	-1.916E-08	-1.892E-06
Total CTG	Total	1.026E+02	2.928E+01	1.277E+00	1.026E+02	2.928E+01	1.277E+00	3.909E+00	4.070E+00	9.151E-03	2.041E-02	1.387E-01	1.202E-04

Figure B.4: Example of embodied energy results generated as a tabulated format from the spreadsheet model.

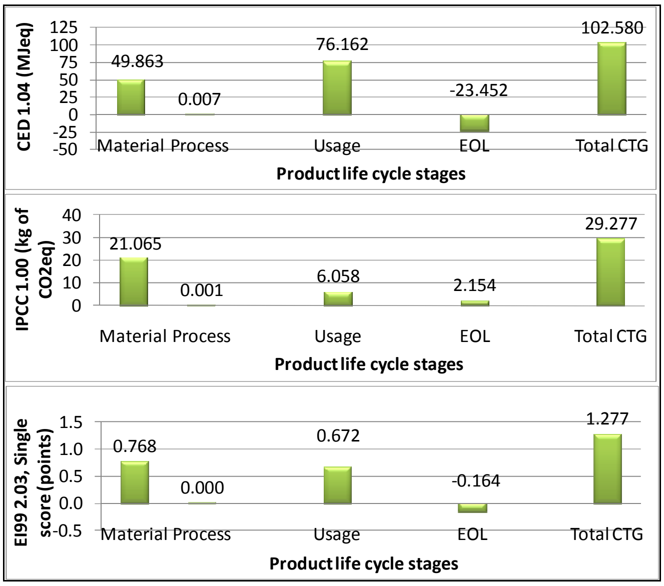
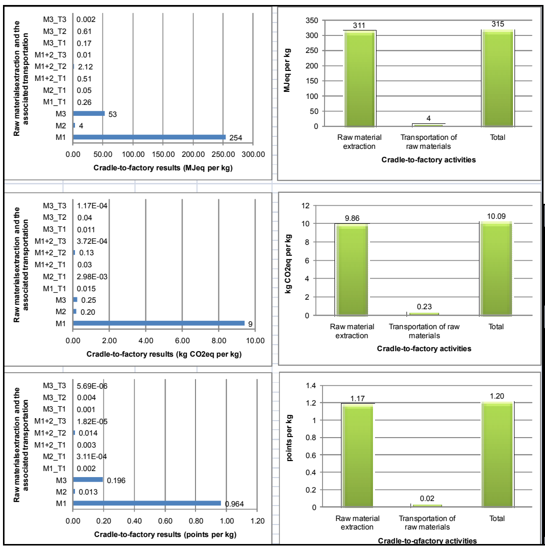


Figure B.5: Example of embodied energy results generated from the spreadsheet model.

Summary of CTF results worksheet:

This worksheet illustrates the summary of the cradle-to-factory analysis as calculated in the 'MODEL' worksheet as shown in Figure B.6.



	Embodied energy result		Full Life Cycle Assessment results
Cradle-to-gate analysis results	Primary energy consumption (MJeq/kg)	Greenhouse gas emissions (kgCO2eq/kg)	Total environmental impacts (points/kg)
aw material extracti	310.7869475	9.85910479	1.173927981
Transportation of raw materials	3.729227131	0.230860841	0.023070021
Total	314.5161747	10.08996563	1.196998002

Raw materials and the associated transportation	Primary energy consumption (MJeq/kg)	Greenhouse gas emissions (kgCO2eq/kg)	Total environmental impacts (points/kg)	Description
M1	254.10	9.41	0.96	Carbon fibre from Wuppertal to Saerbeck: 136km*0.75kg/1000
M2	3.58	0.20	0.01	Nylon stitching from Domat-EMS (Switzerland) to Saerbeck: 812km*0.025kg/1000
M3	53.12	0.25	0.20	Epoxy
M1_T1	0.257151477	0.014967866	0.001560437	Carbon fibre from Wuppertal to Saerbeck: 136km*0.75kg/1000
M2_T1	0.051178187	0.002978899	0.000310558	Nylon stitching from Domat-EMS (Switzerland) to Saerbeck: 812km*0.025kg/1000
M1+2_T1	0.508000222	0.029568872	0.003082628	Carbon fabric from Saerback to Hamburg port: 260km*0.775kg/1000
M1+2_T2	2.116989239	0.1334478	0.013618578	Carbon fabric from Hamburg port to Melbourne port: 29300km 0.775kg
M1+2_T3	0.006049294	0.000372187	1.81527E-05	Carbon fabri: from Port Melbourne to Fisherman bend, VIC: 3.5km*0.775
M3_T1	0.173352897	0.010665651	0.000520198	Epoxy (assumed semi-Trailer) from Bergkamen (GERMANY) to Hamburg (GERMANY) : 320km*0.225kg/1000
M3_T2	0.614609768	0.038742911	0.003953781	Epoxy from Hamburg then shipping to Port Melbourne (AUSTRALIA): 29300km*0.225kg/1000
M3_T3	0.001896047	0.000116656	5.68966E-06	Epoxy from Port MElbourne then (assumed semi-Trailer) to FISHERMENS BEND, VIC: 3.5km*0.225kg/1000
Total	314.52	10.09	1.20	The cradle-to-gate results

Figure B.6: Example of summary of CTF results worksheet.

Summary of CTG results worksheet:

This worksheet illustrates the summary of the cradle-to-grave analysis as calculated in the 'MODEL' worksheet as shown in FigureB.6.

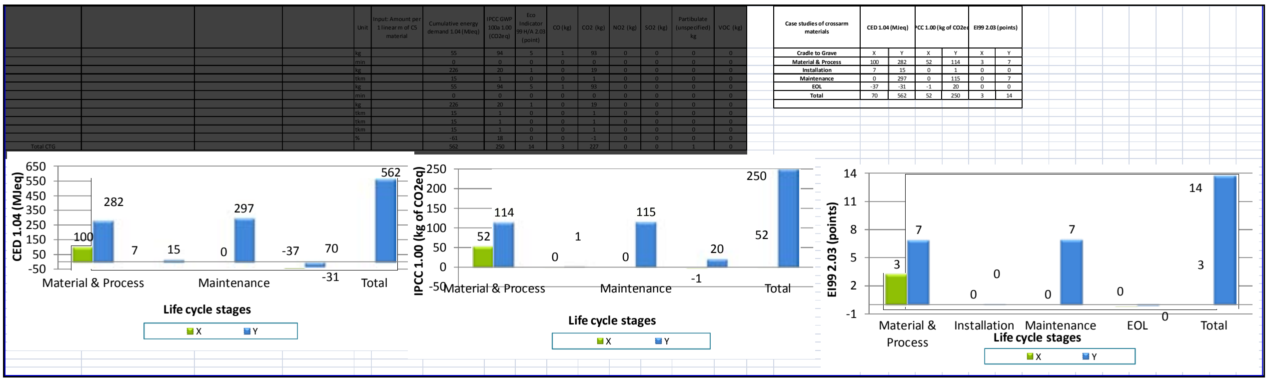


Figure B.7: Example of summary of CTG results worksheet.

The rest of the worksheets as shown in Figure B.8 are the raw data which was generated by the SimaPro software, which are the emission substances results and the detailed results for both composites and traditional products. They are provided as the databases for the 'MODEL' worksheet, in case the user would like to obtain the detailed results for further investigation and reference.

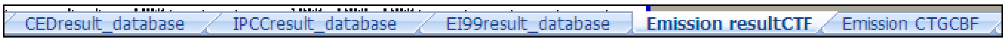


Figure B.8: The rest of the worksheets.

APPENDIX C: GENERAL DATABASE BACKGROUND OF THE EMBODIED ENERGY ANALYSIS

Fibre

Carbon fibre

Documentation | Input/output | Parameters | System description

Project	DTRDI project 2009_final130909	Category	Material
Created on	14/09/2009	Last update on	14/09/2009
Process type	Unit process	Process identifier	Standard19219100234
Name	Carbon fibre		
Status			
Image			

Data Quality Indicators

Time period	1995-1999
Geography	Europe, Western
Technology	Average technology
Representativeness	Average from a specific process
Multiple output allocation	Not applicable
Substitution allocation	Not applicable
Cut-off rules	Less than 5% (physical criteria)
System boundary	Second order (material/energy flows including operations)
Boundary with nature	Unknown
Infra. process	No
Date	12/02/2001
Record	
Generator	Delft University of Technology
Comment	Peebles, L.H., Carbon fibers:formation,structure and properties. Boca Rotan: CRC Press Inc., 1995. energy data from: Lee, S.M. et al., 'The beneficial energy and environmental impact of composite materials-un unexpected bonus' SAMPE Journal vol.27, 1991

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category
Carbon fibre I	1.00000E0	kg	Mass	100 %	Fibres	Fibers
(Insert line here)						

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Bauxite, in ground	in ground	7.77145E-1	kg	Undefined				
Clay, unspecified, in ground	in ground	1.11000E-4	kg	Undefined				
Coal, 29.3 MJ per kg, in ground	in ground	2.18684E0	kg	Undefined				
Gas, natural, 30.3 MJ per kg, in ground	in ground	2.06226E0	kg	Undefined				
Oil, crude, 41 MJ per kg, in ground	in ground	4.49340E-1	kg	Undefined				
Energy, unspecified		1.79452E-1	MJ	Undefined				
Energy, from coal	in ground	5.55000E-1	MJ	Undefined				
Energy, from hydro power	in water	2.90698E-1	MJ	Undefined				
Energy, from gas, natural	in ground	1.23580E1	MJ	Undefined				
Energy, from oil	in ground	1.71717E2	MJ	Undefined				
Energy, from uranium	in ground	3.94108E-2	MJ	Undefined				
Iron ore, in ground	in ground	5.69659E-4	kg	Undefined				
Limestone, in ground	in ground	5.16592E-5	kg	Undefined				
Sodium chloride, in ground	in ground	5.18000E-4	kg	Undefined				
Uranium ore, 1.11 GJ per kg, in ground	in ground	7.97290E-3	kg	Undefined				
Water, unspecified natural origin/kg	in water	7.86478E-2	kg	Undefined				

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
acrylonitrile		3.40000E-4	kg	Undefined				
Arsenic		2.00541E-8	kg	Undefined				
Benzene		6.41730E-5	kg	Undefined				
Cadmium		2.00541E-8	kg	Undefined				
Methane, trichlorofluoro-, CFC-11		2.50000E-5	kg	Undefined				
Methane, dichlorodifluoro-, CFC-12		2.40000E-5	kg	Undefined				
Carbon monoxide		5.07666E-2	kg	Undefined				
Carbon dioxide		1.18664E1	kg	Undefined				
Coal dust		4.10469E-4	kg	Undefined				
Chromium		8.02162E-8	kg	Undefined				
Copper		2.00541E-8	kg	Undefined				
Hydrocarbons, unspecified		1.20036E-2	kg	Undefined				
Cyanide		8.90000E-2	kg	Undefined				
Particulates, SPM		1.40010E-3	kg	Undefined				
Ethane		7.60000E-4	kg	Undefined				
Ethene		3.50000E-4	kg	Undefined				
Hydrogen		9.00000E-3	kg	Undefined				
Hydrogen chloride		2.10196E-5	kg	Undefined				
Heavy metals, unspecified		3.70000E-6	kg	Undefined				
Metals, unspecified		3.68995E-7	kg	Undefined				
Methane		1.20169E-2	kg	Undefined				
Ammonia		4.20000E-2	kg	Undefined				
Nickel		2.00541E-8	kg	Undefined				
Nitrogen dioxide		3.45042E-3	kg	Undefined				
Nitrogen oxides		3.12679E-2	kg	Undefined				
Propane		1.65000E-4	kg	Undefined				
Propene		2.29000E-4	kg	Undefined				
Sulfur dioxide		1.66432E-3	kg	Undefined				
soot		4.63392E-4	kg	Undefined				
Sulfur oxides		1.86957E-2	kg	Undefined				
Toluene		1.56422E-4	kg	Undefined				
water		8.40000E-2	kg	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Acidity, unspecified		1.11000E-4	kg	Undefined				
BOD5, Biological Oxygen Demand		2.03450E-5	kg	Undefined				
Chlorine		4.55963E-5	kg	Undefined				
COD, Chemical Oxygen Demand		4.06899E-5	kg	Undefined				
crude oil		2.36121E-6	kg	Undefined				
Hydrocarbons, unspecified		8.13799E-5	kg	Undefined				
Fluorine		2.33054E-5	kg	Undefined				
Iron		4.29310E-8	kg	Undefined				
Hydrogen		1.31612E-5	kg	Undefined				
Metallic ions, unspecified		2.06823E-5	kg	Undefined				
Ammonia		1.47394E-5	kg	Undefined				
Ammonium, ion		3.70000E-6	kg	Undefined				
Nitrate		3.70000E-6	kg	Undefined				
Nitrogen, total		5.88869E-6	kg	Undefined				
Phenol		6.74630E-8	kg	Undefined				
Suspended substances, unspecified		2.22000E-4	kg	Undefined				

Glass fibre

Project	DTRDI project 2009_final130909	Category	Material
Created on	14/09/2009	Last update on	14/09/2009
Process type		Process identifier	Standard19219100235
Name	Glassfibre I		
Status			
Image			

Data Quality Indicators

Time period	1990-1994
Geography	Europe, Western
Technology	Mixed data
Representativeness	Average of all suppliers
Multiple output allocation	Not applicable
Substitution allocation	Not applicable
Cut-off rules	Unknown
System boundary	Second order (material/energy flows including operations)
Boundary with nature	Unknown
Infra. process	No
Date	10/03/1995
Record	Delft University of Technology
Generator	

General reference and sources

Literature reference	Comment
SPIN Glass (1992)	
Emissieregistratie	VROM 1993
(Insert line here)	

Collection method	
Data treatment	
Allocation rules	
Verification	
Comment	Average of 6 industries in The Netherlands.

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category
Glass fibre I	1	kg	Mass	100 %	Glass	Fibers
(Insert line here)						

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Sand, unspecified, in ground	in ground	0.5672	kg	Undefined				
Sodium hydroxide		0.12	kg	Undefined				soda
Limestone, in ground	in ground	0.08	kg	Undefined				
Dolomite, in ground	in ground	0.04	kg	Undefined				
Feldspar, in ground	in ground	0.04	kg	Undefined				
Gas, natural, 30.3 MJ per kg, in ground	in ground	0.1544	kg	Undefined				
Oil, crude, 42.7 MJ per kg, in ground	in ground	0.0676	kg	Undefined				
Occupation, industrial area	land	0.01	m2a	Undefined				estimate
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Electricity Netherlands ETH I	0.37	MJ	Undefined				

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Sulfur oxides		0.0022	kg	Undefined				
Nitrogen oxides		0.0029	kg	Undefined				
Hydrocarbons, unspecified		0.000009	kg	Undefined				
Carbon monoxide		0.00008	kg	Undefined				
Carbon dioxide		0.4232	kg	Undefined				
Chlorine		0.000076	kg	Undefined				
Fluorine		0.000011	kg	Undefined				
Lead		0.000003	kg	Undefined				
Zinc		0.000007	kg	Undefined				
Particulates, SPM		0.000437	kg	Undefined				
Hydrocarbons, chlorinated		0.000011	kg	Undefined				
Phenol		0.000009	kg	Undefined				
Aldehydes, unspecified		0.000011	kg	Undefined				CH2O
Ammonia		0.000011	kg	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Lead		0.0000000016	kg	Undefined				
Zinc, ion		0.000000032	kg	Undefined				
Sulfate		0.00016	kg	Undefined				
Phosphate		0.000000064	kg	Undefined				
Hydrocarbons, unspecified		0.0000096	kg	Undefined				mineral oil
Fluorine		0.0000157	kg	Undefined				

Resin

Epoxy resin

Project	DTRDI project 2009_final130909	Category	Material
Created on	14/09/2009	Last update on	14/09/2009
Process type		Process identifier	Standard19219100236
Name	Epoxy resin I		
Status			
Image			

Data Quality Indicators

Time period	1990-1994
Geography	Europe, Western
Technology	Mixed data
Representativeness	Theoretical calculation
Multiple output allocation	Socio-economic causality
Substitution allocation	Not applicable
Cut-off rules	Unknown
System boundary	Second order (material/energy flows including operations)
Boundary with nature	Unknown
Infra. process	No
Date	20/02/1996
Record	Delft University of Technology

General reference and sources

Literature reference	Comment
SPIN Shell (1993)	
CHALMERS (1991)	
(Insert line here)	

Collection method	
Data treatment	
Allocation rules	
Verification	
Comment	Assessment based on stoichiometric mix of Epichlorohydrin and Bisphenol A, with n=6. Bispenol A has been derived from PC production. Epichlorohydrin production impacts from Shell. Energy requirement corrected according to Kemna. Low quality.

Documentation | Input/output | Parameters | System description

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category
Epoxy resin I	1	kg	Mass	100 %	Plastics	Plastics\Thermosets
HCl	0.124	kg	Mass	0 %	Others	Chemicals\Acids (inorganic)
(Insert line here)						

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Occupation, industrial area	land	5.57E-3	m2a	Undefined				
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Bisphenol A I	313	g	Undefined				
Epichlorohydrin I	687	g	Undefined				
Crude oil N-sea(b) I	3.9	kg	Undefined				

Unsaturated polyester resin

Documentation | Input/output | Parameters | System description

Project	DTRDI project 2009_final130909	Category	Material
Created on	14/09/2009	Last update on	14/09/2009
Process type		Process identifier	Standard19219100237
Name	Unsaturated polyester		
Status			
Image			

Data Quality Indicators

Time period	1990-1994
Geography	Europe, Western
Technology	Unknown
Representativeness	Average from a specific process
Multiple output allocation	Not applicable
Substitution allocation	Not applicable
Cut-off rules	Unknown
System boundary	Second order (material/energy flows including operations)
Boundary with nature	Unknown
Infra. process	No
Date	29/11/1999
Record	
Generator	

General reference and sources

Literature reference	Comment
Emissieregistratie	process 1851, 1992

Documentation | Input/output | Parameters | System description

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category
Polyester (unsat) I	17346000	kg	Mass	100 %	Plastics	Plastics\Thermosets
(Insert line here)						

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Natural gas I	1354458	kg	Undefined				
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Methane		83.02	kg	Undefined				
Hydrocarbons, aromatic		1575	kg	Undefined				
Nitrogen dioxide		950	kg	Undefined				
Carbon monoxide		367.66	kg	Undefined				
Carbon dioxide		1327.7	ton	Undefined				
(Insert line here)								

Chemicals

Chemicals organic

Documentation | Input/output | Parameters | System description

Name	Chemicals organic ETH
Status	
Image	

Data Quality Indicators

Time period	1990-1994
Geography	Europe, Western
Technology	Average technology
Representativeness	Mixed data
Multiple output allocation	Not applicable
Substitution allocation	Not applicable
Cut-off rules	Unspecified
System boundary	Second order (material/energy flows including operations)
Boundary with nature	Not applicable
Infra. process	No
Date	3/02/2003
Record	PRé Consultants, The Netherlands, MO
Generator	ETH-ESU, Zurich, Switzerland

General reference and sources

Literature reference	Comment
ETH-ESU 1996	Tab. IV.7.13

Comment: Chemicals organic ETH, original German title: Chemikalien organisch.
Unit inventory with links to other processes.
This proces is used to estimate energy consumption of the production of organic materials, when no data are available, or the estimate the size of emissions of chemicals that are used in minor amounts. Estimate based on the production of low density poly ethylene (LDPE). No capital goods included.

Documentation | Input/output | Parameters | System description

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Chemicals organic ETH U	1	kg	Mass	100 %	not defined	Chemicals\Organic	
(Insert line here)							

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Electricity MV use in UCPTE U	8.7E-6	TJ	Undefined				
Residual oil in refinery furnace Europe U	5.9E-5	ton	Undefined				
Refinery gas in furnace Europe U	0.00011	ton	Undefined				
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Heat, waste		8.7E-6	TJ	Undefined				

Chemicals inorganic

Documentation | Input/output | Parameters | System description

Project	DTRDI project 2009_final1DecCheckIEA2_useiea3	Category	Material
Created on	23/12/2009	Last update on	23/12/2009
Process type		Process identifier	Standard21888900612
Name	Chemicals inorganic ETH		
Status			
Image			

Data Quality Indicators

Time period	1990-1994
Geography	Europe, Western
Technology	Average technology
Representativeness	Mixed data
Multiple output allocation	Not applicable
Substitution allocation	Not applicable
Cut-off rules	Unspecified
System boundary	Second order (material/energy flows including operations)
Boundary with nature	Not applicable
Infra. process	No
Date	3/02/2003
Record	PRé Consultants, The Netherlands, MO
Generator	ETH-ESU, Zurich, Switzerland

General reference and sources

Literature reference	Comment
ETH-ESU 1996	Tab. IV.7.13

Comment: Chemicals inorganic ETH, original German title: Chemikalien anorganisch.
Unit inventory with links to other processes.

This proces is used to estimate energy consumption of the production of inorganic materials, when no data are available, or the estimate the size of emissions of chemicals that are used in minor amounts. Estimate based on the production of phosphoric acid. No capital goods included.

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Chemicals inorganic ETH U	1	kg	Mass	100 %	not defined	Chemicals\Inorganic	
(Insert line here)							

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Electricity MV use in UCPTE U	6.0E-7	TJ	Undefined				
Residual oil Europe in boiler 1MW U	5.5E-6	TJ	Undefined				
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^	Min	Max	Comment
Heat, waste		6.0E-7	TJ	Undefined				

Documentation | Input/output | Parameters | System description

System description	Comment
System model Basic Materials	

Description

The system model Basic Materials describes the production of different materials that are used in the life cycle of Western European energy systems. The materials considered are mineralogical materials (sand, gravel, cement, concrete, float glass, mineral wool, lime, limestone, gypsum,
clay, barite, bentonite, ceramics, molecular sieve), inorganic chemicals (chlorine, caustic soda, nitric acid, phosphoric acid, ammonia, iron sulfate,

sodium carbonate, hydrofluoric acid, hydrochloric acid, sulfuric acid, secondary sulfur, urea), organic chemicals (propylene glycol, formaldehyde,

phenols, refrigerants R22 and R134a, soot), metals (iron, steel (low, intermediate and high alloyed), cast iron, aluminium, chromium, manganese,
copper, nickel-pigmented aluminium oxide, hard solder, nickel, rhodium, palladium, platinum, lead, zinc), plastics, rubber and intermediates (polyethylene, polyethylene terephthalate, polypropylene, polystyrene, polyvinylchloride, polycarbonate, polyurethane foam, rubber EPDM), gasses
(hydrogen, nitrogen, oxygen, argon), biogenic materials (paper, cardboard, wood), divers materials and processes (explosives, varnish, water conditioning, galvanizing, sputtering). The inventory tables include resource extraction, refining and production of bulk intermediate products.

Sub-systems

In principle, all subsystems described in System model ESU-ETH 1996 (general principles) are included in the system. Data for individual process steps of producing iron and steel, cast iron, and plastics are recorded individually. For the other materials data from several individual production

steps are aggregated to one single unit process.

Cut-off rules

Infrastructure requirements and land use of material production facilities are not included in the inventory tables. Land use for resource extraction is
considered in most cases.

The production of intermediate products such as Naphtha used for plastics are modeled according to the refinery module described in System model
Energy Carriers.

Varnish includes only NMVOC- and xylene-emissions. Production of varnish is excluded due to missing relevance in relation to its use in energy systems.

The inventory table of hard solder only includes silver and tin (resource consumption only), and copper and zinc (extraction and production included) requirement. No production-specific requirements or emissions are considered.

For construction and working materials standard transport distances are used (see Table 3).

Table 3 Standard transport distances

	Density kg/m3	Supply in Europe Railway (km)	Truck 40 t (km)	Supply in Switzerland Railway (km)	Truck 28 t (km)
Steel/cast iron	7'900	200	100	600	50
Gravel/sand	2'000	20	20		
Cement	3'150	100	50	100	20
Concrete (excl. reinforcing steel)	2'200	20	20		
Floatglass	2'500	600	100	600	50
Copper	8'900	200	100	600	50
Aluminium	2'700	200	100	200	50
Plastics	1)	200	100	200	50

1): PVC: 1'400 kg/m3, PE: 950 kg/m3, PP:900 kg/m3

Allocation rules

Recycled materials, such as iron or copper scrap used in metal production, do not bear any emissions nor resource consumption. The same approach is used for iron sulfate, which is a by-product of pickling rolled iron and where only purification requirements are accounted for. Secondary
sulfur is only charged with energy requirements and its emissions and SOX-emissions during recovery in Claus-units of European refineries.

In iron production a share of blast furnace gas is used for electricity generation. The corresponding share (28% of total blast furnace gas) is subtracted from total emissions of pig-iron production.

Allocation for chlorine, hydrogen and caustic soda is made based on mass.

Within plastics production allocation in the refineries is modeled according to the description given in System model Oil.

In wood production allocation is also necessary. Wood waste from joiner's workshops dedicated for an industrial utilization and used for domestic or
commercial heating is considered as by-product. They do not bear emissions nor resource requirements except the negative CO2-emission.

During ammonia production carbon dioxide is produced which is partly recovered. Here, all CO2 is assumed to be emitted to air (no recovery).

In the combined extraction and refining of platinum group metals (PGM) and nickel, concentration in the ore is used as allocation parameter.

Nitrogen, oxygen and argon (and others) are extracted from air through liquefaction. Mass is used as allocation parameter.
In the production of refrigerants, market values are used as allocation parameter.

Energy model

For aluminium supplied on the European market the electricity mix of the aluminium industry is applied. In all other cases energy and electricity supply is modeled according to the specification described in this section, in System model Energy Carriers, and in System model Electricity, System
model Oil, System model Natural Gas and System model Coal.

Transport model

Required transport means are modeled according to the description given in System model Transports.

Waste model

Only production waste is recorded. End of life waste is recorded in the process where the materials are used. Production waste (if any) are considered with the generic models for waste treatment described in System model Waste Management.

Other assumptions

Land use figures are sometimes estimated based on the average thickness of workable ores.

For some materials only energy consumption figures (electric and thermal) are available. In these cases UCPTE electricity mix and industrial boilers
(oil, gas and coal) are applied.

The inventories are often based on German or Swiss data, which are assumed as an average for Western Europe.

Material production is assumed to happen in the nineties even if the material is used for a dam erected in the early twentieth century.

Other information

Data are recorded in preciseness adequate for its use within life cycle inventories for energy systems. Special emphasis is put on investigating data
for cement, steel, copper, aluminium, glass, platinum group metals and silicon.

For several materials or their ores (iron, aluminium (bauxite), barite, bentonite, gravel and sand, limestone, manganese, copper) land use for extraction has been considered using the average thickness of the mineral ore, the density of the ore and the duration of the extraction. Land use
caused by manufacturing sites is not considered.

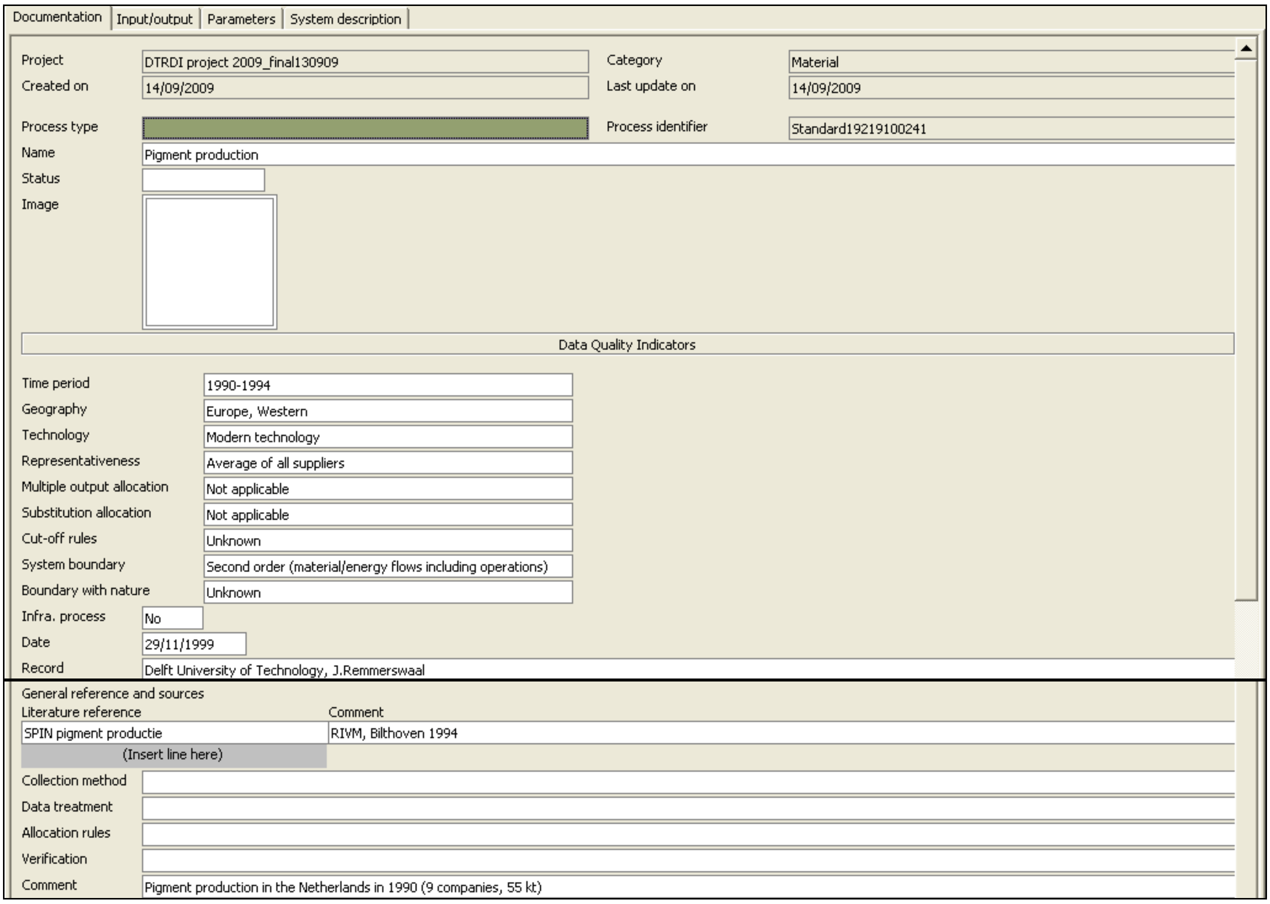
-> Example:
17kg barite ore are required per kg barite. The average thickness is 10m, the density of the ore is 2 tons per m3. Therefore, about 1m2 (rounded to the next order of magnitude) are occupied per ton barite. This surface is used during 10 years of extraction, during 5 years of recultivation from land use category IV to III and 50 years from category III to II (see Table 1).

This leads to 15m2a/kg barite land use II-IV and 50m2a/kg barite land use II-III, assuming that the initial state of the ecosystem (before mining started) was category II.

For a detailed study of material use, e.g. for construction of buildings, it is advised to use specific data sets like, e.g. (WEIBEL & STRITZ 1995).

Processes are extensively described in Appendix A of Frischknecht et al. (1996).

Pigment



Documentation | Input/output | Parameters | System description

Project	DTRDI project 2009_final130909	Category	Material
Created on	14/09/2009	Last update on	14/09/2009
Process type		Process identifier	Standard19219100241
Name	Pigment production		
Status			
Image			

Data Quality Indicators

Time period	1990-1994
Geography	Europe, Western
Technology	Modern technology
Representativeness	Average of all suppliers
Multiple output allocation	Not applicable
Substitution allocation	Not applicable
Cut-off rules	Unknown
System boundary	Second order (material/energy flows including operations)
Boundary with nature	Unknown
Infra. process	No
Date	29/11/1999
Record	Delft University of Technology, J.Remmerswaal

General reference and sources

Literature reference	Comment
SPIN pigment productie	RIVM, Bilthoven 1994
(Insert line here)	

Collection method	
Data treatment	
Allocation rules	
Verification	
Comment	Pigment production in the Netherlands in 1990 (9 companies, 55 kt)

Documentation | Input/output | Parameters | System description

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Pigments (general) I	55000000	kg	Mass	100 %	Others	Chemicals\Others	
(Insert line here)							

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^	Min	Max	Comment
Electricity Netherlands ETH I	2500	TJ	Undefined				
Natural gas I	274337.28	kg	Undefined				
(Insert line here)							

Outputs

Emissions to air

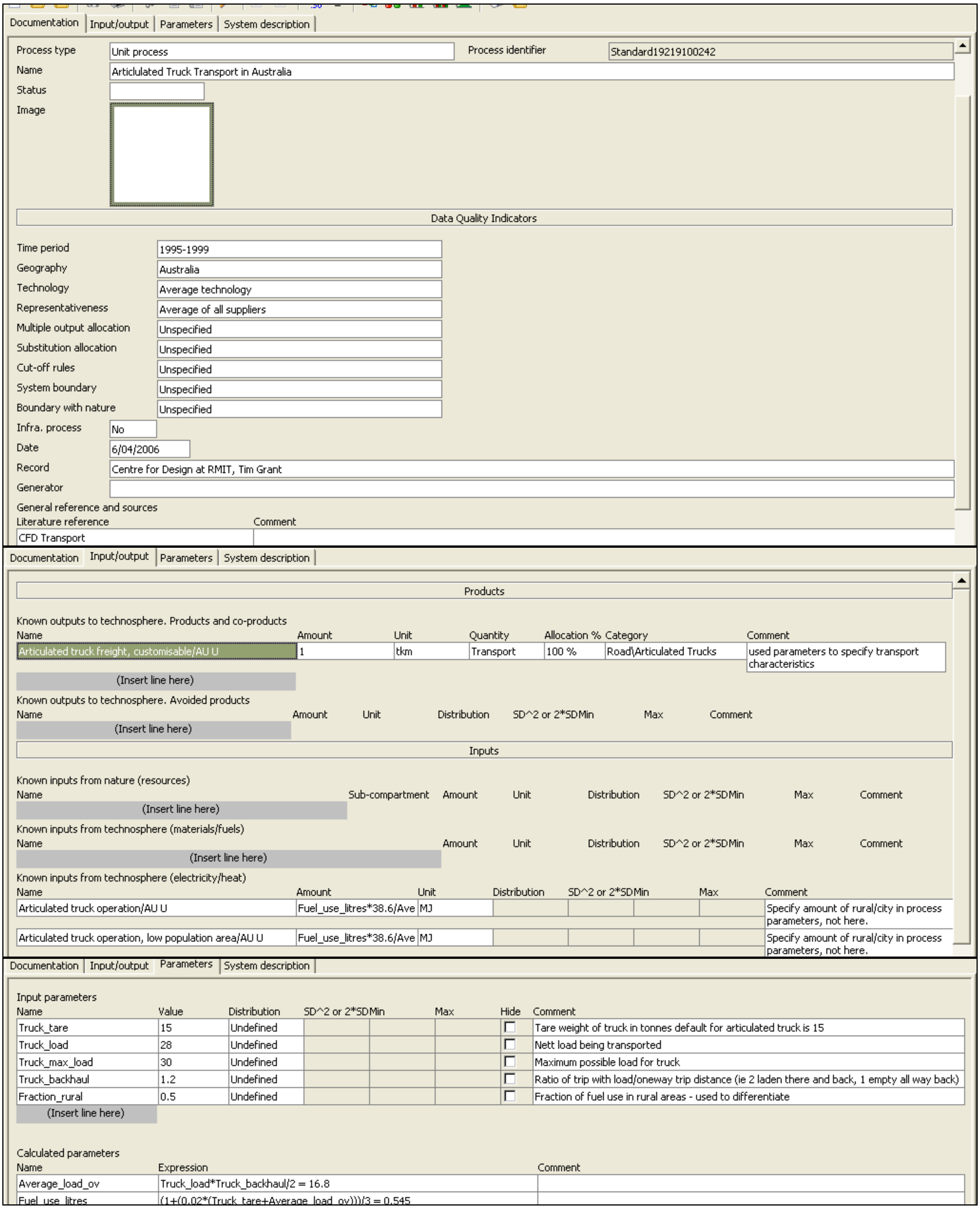
Name	Sub-compartment	Amount	Unit	Distribution	SD^	Min	Max	Comment
Ammonia		0.12	ton	Undefined				
VOC, volatile organic compounds		189	ton	Undefined				
Fluorine		24.2	ton	Undefined				as F-total
Particulates, SPM		2.59	ton	Undefined				
Chromium		0.47	ton	Undefined				
Lead		2.59	ton	Undefined				
Zinc		9.18	ton	Undefined				
Carbon monoxide		33.2	ton	Undefined				
Carbon dioxide		51700	ton	Undefined				
Hydrocarbons, unspecified		3.83	ton	Undefined				
Nitrogen oxides		530	ton	Undefined				
Sulfur dioxide		87.5	ton	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Arsenic, ion		1	kg	Undefined				
Cadmium, ion		24	kg	Undefined				
Chromium		334	kg	Undefined				
Copper, ion		28	kg	Undefined				
Fluorine		1330	kg	Undefined				
Nitrogen, total		778	ton	Undefined				
Nickel, ion		180	kg	Undefined				
Lead		977	kg	Undefined				
Phosphorus, total		1500	kg	Undefined				
Sulfur		71400	kg	Undefined				
Zinc, ion		597	kg	Undefined				
COD, Chemical Oxygen Demand		11.9	ton	Undefined				
Hydrocarbons, unspecified		11.9	ton	Undefined				
Suspended solids, unspecified		35.4	ton	Undefined				

Transportation

Articulated truck



Documentation | Input/output | Parameters | System description

Process type	Unit process
Process identifier	Standard19219100242
Name	Articulated Truck Transport in Australia
Status	
Image	

Data Quality Indicators

Time period	1995-1999
Geography	Australia
Technology	Average technology
Representativeness	Average of all suppliers
Multiple output allocation	Unspecified
Substitution allocation	Unspecified
Cut-off rules	Unspecified
System boundary	Unspecified
Boundary with nature	Unspecified
Infra. process	No
Date	6/04/2006
Record	Centre for Design at RMIT, Tim Grant
Generator	

General reference and sources

Literature reference	Comment
CFD Transport	

Documentation | Input/output | Parameters | System description

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Category	Comment
Articulated truck freight, customisable/AU U	1	tkm	Transport	100 %	Road\Articulated Trucks	used parameters to specify transport characteristics
(Insert line here)						

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Articulated truck operation/AU U	Fuel_use_litres*38.6/Ave	MJ					Specify amount of rural/city in process parameters, not here.
Articulated truck operation, low population area/AU U	Fuel_use_litres*38.6/Ave	MJ					Specify amount of rural/city in process parameters, not here.

Documentation | Input/output | Parameters | System description

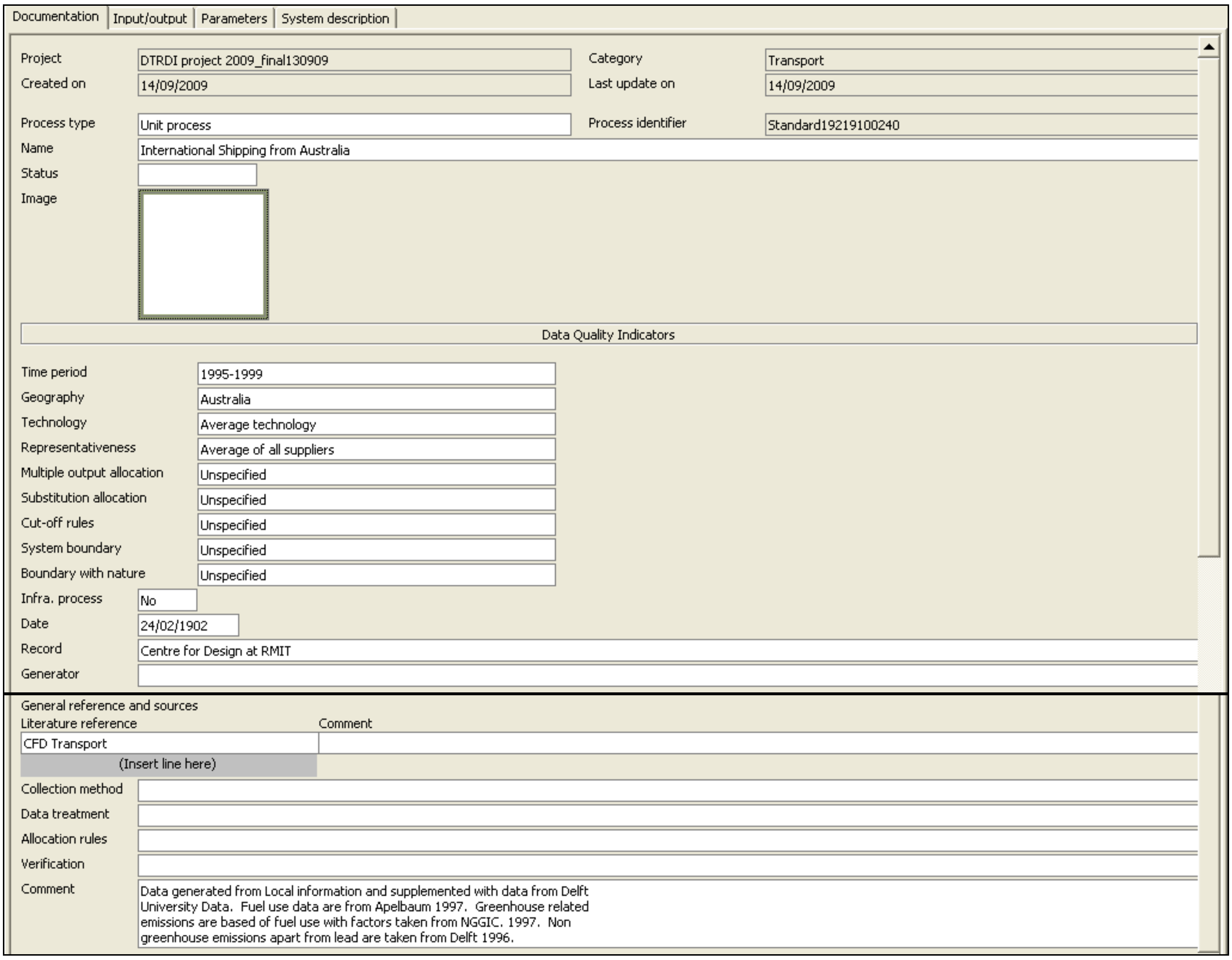
Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
Truck_tare	15	Undefined				☐	Tare weight of truck in tonnes default for articulated truck is 15
Truck_load	28	Undefined				☐	Nett load being transported
Truck_max_load	30	Undefined				☐	Maximum possible load for truck
Truck_backhaul	1.2	Undefined				☐	Ratio of trip with load/oneway trip distance (ie 2 laden there and back, 1 empty all way back)
Fraction_rural	0.5	Undefined				☐	Fraction of fuel use in rural areas - used to differentiate
(Insert line here)							

Calculated parameters

Name	Expression	Comment
Average_load_ov	Truck_load*Truck_backhaul/2 = 16.8	
Fuel_use_litres	(1+(0.02*(Truck_tare+Average_load_ov)))/3 = 0.545	

International shipping



Documentation | Input/output | Parameters | System description

Project	DTRDI project 2009_final130909
Created on	14/09/2009
Category	Transport
Last update on	14/09/2009
Process type	Unit process
Process identifier	Standard19219100240
Name	International Shipping from Australia
Status	
Image	

Data Quality Indicators

Time period	1995-1999
Geography	Australia
Technology	Average technology
Representativeness	Average of all suppliers
Multiple output allocation	Unspecified
Substitution allocation	Unspecified
Cut-off rules	Unspecified
System boundary	Unspecified
Boundary with nature	Unspecified
Infra. process	No
Date	24/02/1902
Record	Centre for Design at RMIT
Generator	

General reference and sources

Literature reference	Comment
CFD Transport	
(Insert line here)	

Collection method	
Data treatment	
Allocation rules	
Verification	
Comment	Data generated from Local information and supplemented with data from Delft University Data. Fuel use data are from Apelbaum 1997. Greenhouse related emissions are based of fuel use with factors taken from NGGIC. 1997. Non greenhouse emissions apart from lead are taken from Delft 1996.

Documentation | Input/output | Parameters | System description

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Category	Comment
Shipping, international freight/AU U	1	tkm	Transport	100 %	Water	
(Insert line here)						

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^	Min	Max	Comment
Diesel, at consumer/AU U	0.12	g	Undefined				0.01MJ. Energy use factors from Abelbaum 1997
Fuel oil, at consumer/AU U	0.98	g	Undefined				0.04MJ Energy use factors from Abelbaum 1999
Transport infrast. priv. sect/AU U	0.014	MJ	Undefined				Based on Ratio of direct energy to infrastructure energy of 30%- from Lenzen 1999
Transport infrast. pub sect/AU U	0.002	MJ	Undefined				Based on Ratio of direct energy to infrastructure energy of 5%- from Lenzen 1999
(Insert line here)							

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^	Min	Max	Comment
Carbon dioxide		3.4	g	Undefined				NGGIC 1997 data (table 1A5) for fuel use in provided by Apelbaum 1997
Methane	low. pop.	0.02	g	Undefined				NGGIC 1997 data (table 1A5) for fuel use in provided by Apelbaum 1997

Documentation | Input/output | Parameters | System description

Name	Sub-compartment	Amount	Unit	Distribution	SD^	Min	Max	Comment
Carbon dioxide		3.4	g	Undefined				NGGIC 1997 data (table 1A5) for fuel use in provided by Apelbaum 1997
Methane	low. pop.	0.02	g	Undefined				NGGIC 1997 data (table 1A5) for fuel use in provided by Apelbaum 1997
Nitrogen oxides	low. pop.	0.092	g	Undefined				NGGIC 1997 data (table 1A5) for fuel use in provided by Apelbaum 1997
Carbon monoxide	low. pop.	0.003	g	Undefined				NGGIC 1997 data (table 1A5) for fuel use in provided by Apelbaum 1997
NMVOC, non-methane volatile organic compounds, unspecified origin	low. pop.	0.003	g	Undefined				NGGIC 1997 data (table 1A5) for fuel use in provided by Apelbaum 1997
Sulfur oxides		0.065	g	Undefined				Table 1, workbook 3.1 Suppliment, NGGIC 1997
Particulates, < 10 um	low. pop.	3.4	mg	Undefined				Taken from Delft 1996 data for Cargo ship and proportioned to fuel use.
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Economic issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
AU database, energy end use indicator, transport energy		0.0474	MJ	Undefined				

Electricity

Electricity, High Voltage, Australian Average

Name	Electricity HV
Status	
Image	

Data Quality Indicators

Time period	2000-2004
Geography	Australia
Technology	Average technology
Representativeness	Average of all suppliers
Multiple output allocation	Physical causality
Substitution allocation	Not applicable
Cut-off rules	Not applicable
System boundary	Third order (including capital goods)
Boundary with nature	Agricultural production is part of production system

Comment: Use this as the main inventory for Australian electricty. It can be swithed between unit and system processes, depending on user assessment needs

Products

Known outputs to technosphere. Products and co-products

Name	Amou	Unit	Quantity	Allocation %	Category	Comment
Electricity, high voltage, Australian average/AU U	1	GWh	Energy	100 %	Electricity country mix\Australian	
(Insert line here)						

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Electricity, high voltage, Australian average, production/AU U	1	GWh	Undefined				

Electricity, Low Voltage, Queensland/ AU U

Data Quality Indicators

Time period	2000-2004
Geography	Australia
Technology	Average technology
Representativeness	Average of all suppliers
Multiple output allocation	Socio-economic causality
Substitution allocation	Not applicable
Cut-off rules	Not applicable
System boundary	Third order (including capital goods)
Boundary with nature	Not applicable
Infra. process	No
Date	12/08/2004
Record	Tim Grant
Generator	

General reference and sources

Literature reference	Comment
ESAA 2003	
(Insert line here)	

Collection method	
Data treatment	
Allocation rules	
Verification	
Comment	This inventory distribution of electricity in Australia in 1995/96 wih distribution losses included. To be used for low voltage domestic electricity supply.

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Category	Comment
Electricity, low voltage, Queensland/AU U	0.94	kWh	Energy	100 %	...\State based low voltage	Distribution losses of 6%
(Insert line here)						

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Mi	M	Comment
Electricity, high voltage, Queensland/AU U	1	kWh	Lognormal	1.05			Estimate of line loss variabilit

Disposal process

Modified Household waste /AU U

Name: Household waste (consumer waste) Australia

Comment: This record contains average behavioural scenario for Australian households for separation of waste (glass, paper, etc.) before it is collected by the municipality. Roughly based on Melbourne BIEC data 1997. Should be tailored to individual project

Name	Amount	Unit	Category	Comment
Household waste/AU U_DTRDI_ti100	1	kg	Household	

Inputs

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Mi	M	Comment
(Insert line here)							

Outputs

Materials and/or waste types separated from waste stream

Waste scenario/treatment	Material / Waste type	Percentage	Comment
Recycling tinplate, from kerbside/AU U	Ferro metals	44 %	
Recycling steel, structural applications/AU U	Ferro metals	70 %	
Recycling steel, sheet steel/AU U	Steel sheet	70 %	
Recycling steel, structural applications/AU U	Steel	70 %	
Recycling recycled steel/AU U	Steel, recycled	70 %	
Recycling Aluminium/AU U	Aluminium	65 %	
Recycling titanium FN	Titanium I	100 %	From the machinging process
No treatment/AU U	Water	100 %	
(Insert line here)			

Waste streams remaining after separation

Waste scenario/treatment	Percentage	Comment
Landfill/AU U	100 %	all materials not separated above is treated as municipal waste