The Application of Life Cycle Assessment to Metal Casting

by

Theodoros Staikos

A Master's Thesis
Submitted in partial fulfilment of the requirement for the award of the degree of Master of Philosophy of Loughborough University

October 2003

NO STAMP.

Acknowledgement

I would like to thank everyone that participated in this study Especially, I would like to acknowledge my supervisor Dr Allen J Clegg for his supervision, discussions and proofreading during the work of this thesis

Financial support that has been provided by the European Union through a Fifth Framework Programme (GROWTH) contract to conduct this research work is gratefully acknowledged

Many thanks also to my family for their support all these years

Preface

The thesis was prepared in a time spanning from October 2002 until beginning of November 2003. The opportunity to submit this MPhil thesis arose from my involvement, as a research assistant at Loughborough University, in a EU-funded research project called "*New Dispersion Strengthened Low Cost Ductile Iron for Light-Weight Components*" (DILIGHT).

Loughborough University was one of the six European partners in the DILIGHT consortium that includes universities, research institutes and industrial companies in Germany, Italy and Norway. The DILIGHT project aims to develop a new grade of ductile cast iron for lightweight design of automotive components. One of the major objectives of the project was to quantify the potential environmental impacts of the new DILIGHT alloy throughout its life cycle and to compare these with those of existing and alternative competing alloys.

The specific objective of my research at Loughborough University was to conduct Life Cycle Assessment (LCA) studies of specific automotive components cast in traditional cast iron, aluminium alloy and the new 'DILIGHT' alloy in order to identify the best environmental proposition. Loughborough University was intimately connected with the Research Centre of FIAT (CRF) in Italy. These two institutions were responsible for the entire Life Cycle Assessment workpackage, though, Loughborough University was the workpackage leader.

Additionally, three conference papers were published based on the original research work:

1. *"Potential for Vehicle Weight Reduction Using a New Ductile Cast Iron"* presented by myself at the "Second International Conference on Design and Manufacture for Sustainable Development" at Cambridge University on September 3-4, 2003.
2. *"Incorporating Life Cycle Assessment within the Teaching of Sustainable Design"* presented by myself at the "2003 International Engineering and Product Design Education Conference" at Bournemouth University on September 10-11, 2003.
3. *"Reducing the Environmental Impacts of Metal Castings through Life-cycle Management"* presented by my supervisor Dr Allen J Clegg at the "2003 Business Strategy and Environment Conference" at Leicester University on September 16, 2003

These conference papers can be seen in the Appentices XI, XII and XIII.

Table of Contents

Acknowledgement i
Preface ii
List of Figures vi
List of Tables vii
Abstract viii
Chapter 1. Introduction 1
  1.1 Introduction 1
  1.2 Vehicle Weight Reduction Using Lightweight Materials 2
  1.3 The Role of Life Cycle Assessment 3
  1.4 Research Context 3
    1.4.1 Problem Formulation 4
    1.4.2 Objectives of the Research 4
  1.5 Research Methodology 5
  1.6 Structure of the Thesis 5
Chapter 2. Automotive Casting Materials and Processes 7
  2.1 Casting Materials 7
    2.1.1 Grey Iron Castings 8
    2.1.2 Ductile Iron Castings 8
    2.1.3 Malleable Iron Castings 8
    2.1.4 Aluminium Alloy Castings 9
  2.2 Casting Processes 9
  2 3 The UK Foundry Industry 11
    2.3.1 Environmental Overview of the UK Foundry Industry 11
    2.3.2 Market Pressures 12
  2.4 Metal Castings for the Automotive Industry 13
    2.4.1 Automotive Casting Applications 13
    2.4.2 Automotive Light Weighting Initiatives 14
    2.4.3 Current Trends in Automotive Casting Applications 15
Chapter 3. Life Cycle-Based Concepts and Tools 16
  3.1 Concepts and Tools. 16
  3.2 Life Cycle Assessment 18
    3.2.1 Life Cycle Assessment Framework 18
      3.2.1.1 Goal and scope definition 19
      3.2.1.2 Inventory analysis 20
      3.2.1.3 Impact assessment 20
      3.2.1 4 Interpretation 20
    3.2.3 LCA as a Tool to Justify Environmental Superiority 20
  3.3 Critical Summary 22
Chapter 4 Life Cycle Assessment Methodology 23
  4.1 Goal and Scope Definition 23
    4.1.1 Function and Functional Unit 23
    4.1.2 Initial System Boundaries 24
    4.1.3 Limitations of the LCA study 26
    4.1.4 Key Assumptions 26
      Weight of the Functional Unit 26
      Percentage of Virgin and Secondary Materials 27
      Exclusion of Minor Life Cycle Stages from LCI Calculations 27

4.2 Life Cycle Inventory Analysis 27
  4.2.1 Material Production 28
    Aluminium Alloy Product System 28
    Cast Iron Product System 29
  4.2.2 Foundry Process 30
    Aluminium Alloy Product System 31
    Cast Iron Product System 32
  4.2.3 Manufacturing and Assembly 32
  4.2.4 Auto Use Phase 34
  4.2.5 End-of-Life Management 35
4.3 Summary 36
Chapter 5. Results: Life Cycle Impact Assessment 37
5.1 Selection of Impact Categories and Category Indicators 37
5.2 Classification and Characterization 38
  5.2.1 Global Warming Potential 38
    5.2.1.1 Aluminium Alloy Product System 38
      Base Case Scenario 38
      Alternative Life Cycle Scenarios 39
    5.2.1.2 Cast Iron Product System 39
      Base Case Scenario 39
      Alternative Life Cycle Scenarios 39
  5.2.2 Acidification Potential 40
    5.2.2.1 Aluminium Alloy Product System 40
      Base Case Scenario 40
      Alternative Life Cycle Scenarios 41
    5.2.2 2 Cast Iron Product System 41
      Base Case Scenario 41
      Alternative Life Cycle Scenarios 41
  5.2.3 Photo-Oxidant Formation 42
    5.2.3.1 Aluminium Alloy Product System 42
      Base Case Scenario 42
      Alternative Life Cycle Scenarios 43
    5.2.3.2 Cast Iron Product System 43
      Base Case Scenario ... .43
      Alternative Life Cycle Scenarios 43
  5.2.4 Energy Consumption 44
    5.2.4.1 Aluminium Alloy Product System 44
      Base Case Scenario 44
      Alternative Life Cycle Scenarios 44
    5.2.4.2 Cast Iron Product System 45
      Base Case Scenario 45
      Alternative Life Cycle Scenarios 45
5.3 Summary 46
Chapter 6. Analysis Interpretation Phase 47
6.1 Contribution Analysis 47
  6.1.1 Global Warming Potential 48
    6.1.1.1 Aluminium Alloy Product System 48
      Base Case Scenario 48
      Alternative Life Cycle Scenarios 49
    6.1.1.2 Cast Iron Product System 50

Base Case Scenario 50
Alternative Life Cycle Scenarios 50
6.1.2 Energy Consumption 51
6.1.2.1 Aluminium Alloy Product System 51
Base Case Scenario 51
Alternative Life Cycle Scenarios 52
6.1.2.2 Cast Iron Product System 53
Base Case Scenario 53
Alternative Life Cycle Scenarios 54
6.2 Comparison of Product Systems 55
6.2.1 Comparability of the Product Systems 56
6.2.2 Global Warming Potential 56
Base Case Scenario 56
Alternative Life Cycle Scenarios 57
6.2.3 Energy Consumption 58
Base Case Scenario 58
Alternative Life Cycle Scenarios 59
6 2.4 Break-Even Point 60
Base Case Scenario 60
1st Life Cycle Scenario 61
2nd Life Cycle Scenario 62
3rd Life Cycle Scenario 62
4th Life Cycle Scenario 63
6.3 Discussion of the Results 64
6.3.1 Material Production Phase 66
6.3.2 Foundry Process 66
6.3.3 Auto Use Phase 66
6.4 Strengths and Weaknesses of the LCA Methodology 67
6.5 Summary 67
Chapter 7. Conclusions and Recommendations 69
7.1 Conclusions 69
7.2 Suggestions for Further Research 70
References 72
Appendix I 75
Appendix II 79
Appendix III 83
Appendix IV 87
Appendix V 91
Appendix VI 95
Appendix VII 99
Appendix VIII 103
Appendix IX 107
Appendix X 111
Appendix XI 115
Appendix XII 128
Appendix XIII 137

List of Figures

Figure 1: Overall Foundry Sector Mass Balance 12
Figure 2: Concepts and Tools for Sustainable Development 17
Figure 3: LCA Framework 19
Figure 4: Aluminium Alloy Suspension Arm 24
Figure 5: Life Cycle Stages of an Automotive Suspension Arm 25
Figure 6: Aluminium Material Production Process Flow Diagram 29
Figure 7: Cast Iron Material Production Process Flow Diagram 30
Figure 8: Aluminium Foundry Process Flow Diagram 31
Figure 9: Cast Iron Foundry Process Flow Diagram 32
Figure 10: Manufacturing and Assembly Process Flow Diagram 33
Figure 11: Auto Use Phase Flow Diagram 35
Figure 12: End-of-Life Management Process Flow Diagram 36
Figure 13: Aluminium Alloy GWP from a Life Cycle Stages Perspective 48
Figure 14 Aluminium Alloy GWP from a Life Cycle Stages Perspective (Alternative Scenarios) 49
Figure 15: Cast Iron GWP from a Life Cycle Stages Perspective 50
Figure 16: Cast Iron GWP form a Life Cycle Stages Perspective (Alternative Scenarios) 51
Figure 17: Energy Consumption for the Aluminium Alloy Product System 52
Figure 18: Energy Consumption for the Aluminium Alloy Product Systems (Alternative Scenarios) 53
Figure 19: Energy Consumption for the Cast Iron Product System 54
Figure 20: Energy Consumption for the Cast Iron Product Systems (Alternative Scenarios) 55
Figure 21: Comparative Global Warming Potential 57
Figure 22: Comparative Global Warming Potential (Alternative Scenarios) 58
Figure 23: Comparative Energy Consumption 59
Figure 24: Comparative Energy Consumption (Alternative Scenarios) 59
Figure 25: Break-Even Point Between Aluminium and Cast Iron 60
Figure 26: Break-Even Point Between Aluminium and Cast Iron (1st Scenario) 61
Figure 27: Break-Even Point Between Aluminium and Cast Iron (2nd Scenario) 62
Figure 28: Break-Even Point Between Aluminium and Cast Iron (3rd Scenario) 63
Figure 29: Break-Even Point Between Aluminium and Cast Iron (4th Scenario) 64

List of Tables

Table 1: Type of Casting Metals 7
Table 2: Metal Casting Processes 10
Table 3: Metals used in UK Casting Processes 11
Table 4: Classification of Automotive Casting Applications 13
Table 5: Material and Weight of Suspension Arms 24
Table 6: Different Life Cycle Scenarios 27
Table 7: Selected Impact Categories and Category Indicators 37
Table 8: Aluminium Alloy Global Warming Potential 38
Table 9: Aluminium Alloy Global Warming Potential (Alternative Scenarios) 39
Table 10: Cast Iron Global Warming Potential 39
Table 11: Cast Iron Global Warming Potential (Alternative Scenarios) 40
Table 12: Aluminium Alloy Acidification Potential 40
Table 13: Aluminium Alloy Acidification Potential (Alternative Scenarios) 41
Table 14: Cast Iron Acidification Potential 41
Table 15: Cast Iron Acidification Potential (Alternative Scenarios) 42
Table 16: Aluminium Alloy Photo-Oxidant Formation 42
Table 17: Aluminium Alloy Photo-Oxidant Formation (Alternative Scenarios) 43
Table 18: Cast Iron Photo-Oxidant Formation 43
Table 19: Cast Iron Photo-Oxidant Formation (Alternative Scenarios) 44
Table 20: Aluminium Alloy Energy Consumption 44
Table 21: Aluminium Alloy Energy Consumption (Alternative Scenarios) 45
Table 22: Cast Iron Energy Consumption 45
Table 23: Cast Iron Energy Consumption (Alternative Scenarios) 46
Table 24: Potential Contribution of the Different Life Cycle Stages to Global Warming 65
Table 25: Energy Consumption Contribution of the Different Life Cycle Stages 65

Abstract

The thesis presents a Life Cycle Assessment (LCA) study that compares the potential environmental impacts associated with two alternative material groups. The comparison involves aluminium alloy and cast iron automotive casting components. The comparative LCA study aims to identify which system of materials, aluminium or cast iron, reduces the total burdens on the environment most throughout the entire lifecycle of a metal casting automotive application. A specialised LCA software tool (Boustead Model 4.4) has been used to compare and contrast the potential environmental impacts of the two alternative cast metal alloys and, conclusively, identify the best environmental proposition for the specific metal casting application.

The study follows the terminology developed by the International Organization for Standardization (ISO) 14040 standards. The assessment considers the whole life cycle of the competing materials from the extraction and production of raw materials, the foundry processing, the auto use phase and, finally, the end-of-life treatment of the automotive casting components. However, the LCA study was focused on processes and life cycle stages where preliminary calculations or earlier experience indicate that the difference in potential environmental impacts can be significant between the two alternative choices. In this context, the study assumed that the manufacturing and assembly and the end-of-life management phases have similar industrial processes for both aluminium and cast iron product systems and, consequently, discharge almost the same amount of pollution. As a result, these two life cycle stages were excluded from the calculations of the life cycle inventory within the current study. For comparability reasons, the same functional unit has been used in the studies for each product system: an automotive suspension arm. This ensures that the functional unit was well defined and that the two alternatives were comparable. Finally, the initial LCA study (base case scenario) assumed that 100% virgin material was used in order to produce the two alternative suspension components. However, cast iron and aluminium castings used in automotive components typically contain 60 to 70% of secondary material. To accommodate this, the study examined four different life cycle scenarios in a sensitivity analysis. These scenarios calculate the replacement of primary material by secondary sources resulting from recycling of metal scrap.

One of the main conclusions of the base case scenario was that the benefits to the environment of substituting aluminium for cast iron are not significant until the vehicle has travelled 250,000 km. On the other hand, the four life cycle scenarios showed that wide variations apply when secondary material is used. The aluminium alloy suspension arm is likely to be more environmentally superior than the cast iron alternative as long as the percentage of secondary material is increased For example, when secondary aluminium and cast iron replace 75% of primary materials then the break-even point between the two alternative material groups reduced to just under 100,000 km.

Chapter 1. Introduction

1.1 Introduction

Scientists, policy-makers, and the general public are becoming increasingly aware of environmental damage associated with large and growing material consumption required in our modern society. The industrial sector is under increasing pressure to reduce its current level of material consumption and minimize its harmful releases to air, water and land. These developments are promoting a radical transformation of the industrial domain towards proactive approaches that deal with industrial pollution and, consequently, protect the environment as a whole. The so-called "ecological" transformation of the industrial sector can be seen as adjustments that emerge through the market and push industries towards technological and institutional changes in order to adopt integrated approaches of dealing with pollution while at the same time opening up new market opportunities for the entire sector (Dryzek, 1997, p. 21).

One of the largest and most complex industrial sectors on a global scale is the automotive industry. It contributes 4% to 8% of the Gross Domestic Product (GDP) and accounts for 2% to 4% of the labour force in the Organization of Economic Co-operation and Development (OECD) countries (UNEP, 2002). In the European Union (EU), 1.2 million people are employed in jobs that are directly related to vehicle manufacturing while another 12 million people are employed in jobs that are indirectly related to this specific industrial sector (UNEP, 2002). The industrial system that produces vehicles is vast in both economic and absolute terms. The vehicle manufacturers, consumers, and regulators comprise the key stakeholders of the automobile industrial system. However, this system also includes the raw material suppliers, parts fabricators, service and repair professionals, dismantlers, shredders, waste managers, insurers, and investors (Bulkley et al., 1997). Each stakeholder is responsible for contributing to activities that adversely affect the environment and public health through the production of waste products and emissions. Therefore, any change in automotive design, material, engineering, or regulation aimed at improving one aspect of the industrial system should also be evaluated for its impacts on other system components.

The increase of worldwide automobile usage has resulted in the rise of the associated environmental problems. These include global warming potential, air pollution, acidification, ozone depletion and disposal of waste. However, the most serious environmental problem facing the automobile is its enormous consumption of non-renewable energy during its use phase. Motor vehicles burn fossil fuels and therefore are a significant source of carbon dioxide (CO_2) emissions, the main greenhouse gas responsible for man-made global climate change. Road transport accounts for 22 % of the total CO_2 emissions in the EU and this has grown by around 9% from 1990 to 1997. Passenger vehicles account for much of this growth (EC, 2000). Additionally, emissions from road transport are projected to continue to increase in Europe up to 2010, due to continued increases in both passenger and freight transport carried out by road (European Environmental Agency, 2002). Consequently, it is not surprising that the automobile industry is subjected to continuing market and regulatory pressures to manage its greenhouse gas emissions and therefore produce more environmentally friendly products.

In this context, the automobile manufacturers and their suppliers have taken their own environmental initiatives concerning the whole life cycle of motor vehicles. Although significant environmental improvements in vehicle design and production have already been achieved, there is a strong need for further fuel economy improvements. Direct improvements in fuel economy can be achieved through greater engine or power train efficiency as well as reduced air resistance. Indirect improvements can be achieved through weight reduction, the so-called light weighting.

Therefore the problem of fuel consumption and vehicle weight reduction has come to the fore. Reducing the weight of automobiles is one of the primary means by which their fuel consumption can be lowered. The environmental aspect of vehicle weight reduction is visible through a reduction in air pollution, especially CO_2 emissions, as a result of the reduced fuel consumption due to the reduced car weight. Vehicle mass is the single most important factor in improved fuel economy since a 1% mass reduction yields a 0.6% fuel economy improvement (Jenssen, Thiel, 2000). Light weighting brings many economic and environmental benefits to the car manufacturer and the consumer, which will become increasingly important as competitive pressures become stronger. Additionally, reducing the weight of certain parts of the car helps the automobile industry to fulfil their need to compensate for the weight they are increasingly adding in the form of equipment to enhance safety and comfort standards of their car models.

Vehicle weight reduction and, more specifically, light weighting requirements are passing down the supply chain to the main component suppliers. Most automobile manufacturers purchase their components from first tier suppliers who in turn purchase inputs from secondary tier suppliers. The metal casting industry is one of the major suppliers of automotive components that provide the car manufacturers with crucial automotive parts such as engine blocks, crankshafts, camshafts, transmission housings, cylinder heads, and suspension components. In fact, the automotive industry is the most significant of all end-use markets for the foundry industry, purchasing more than one-third of all metal castings shipped each year (Sustainable Industry, 1998, p.6). Moreover, the automotive industry and their casting suppliers quite often join forces in new research projects to initiate advancements in processes and materials that spread out across other industries (Lessiter, 2000)

1.2 Vehicle Weight Reduction Using Lightweight Materials

The two basic approaches to achieve vehicle weight reductions can be found in the areas of automotive design and materials selection. The design approaches include improved aerodynamic design as well as reduced rolling resistance from reduced friction between the vehicle and the road. On the topic of materials selection, there has been a trend towards the use of lightweight metals and their alloys in automotive components, especially automotive bodies. While many of these measures have already been used in production vehicles, the only area that promises significant improvements in fuel economy in the future is the use of lightweight materials for automotive components.

The weight of the vehicle can be substantially reduced by replacing certain of its parts, originally manufactured in one type of metal, by others manufactured out of lighter metals such as aluminium and magnesium alloys or even composite materials. In addition to the development of completely new lighter materials for automotive applications there is of course a continual gradual improvement in the properties of the materials that have been traditionally used by the industry such as steel and cast iron alloys for automobile components. Finally, economic considerations and recycling issues play an important role in the material selection process and often limit the application of the new lighter materials in the automotive sector.

1.3 The Role of Life Cycle Assessment

Because material selection affects to a great extent the entire vehicle life cycle, systems analysis tools are essential to achieve aggregate reductions in environmental burdens as well as compare different product systems. Life Cycle Assessment (LCA) is such a system analysis tool that can be used to assess the environmental aspects and potential impacts associated with a product system[1]

LCA gives a holistic view of the impacts associated with a product system during the whole span of life ("from cradle to grave") In this context, LCA methodology can be applied to support the choice of materials for automotive components. For example, environmental burdens caused by lightweight metals can be compared with those caused by traditional metals. In addition, LCA procedures can be used to evaluate environmental metrics such as global warming potential, acidification potential, and, air, water and solid emissions associated with the industry.

1.4 Research Context

As competitive pressures to improve the fuel-efficiency of motor vehicles intensify for the automotive industry, it is the casting component manufacturers who are in the direct firing line. The automotive industry is placing ever greater demands on its casting suppliers to reduce the weight of their products and therefore to contribute to overall reduced vehicle weight.

---

[1] The term product system includes not only products but also processes and services

The trend towards smaller, lighter, and more fuel-efficient vehicles has caused a significant increase in the production of lighter non-ferrous castings such as aluminium alloys. On the other hand there has been strong competition from the ferrous foundries, which for obvious reasons would prefer that cast iron and steel be retained as the primary automotive material

Lightweight castings using aluminium can reduce the overall fuel consumption of automobiles significantly. However, the primary energy requirement for the production of aluminium is ten times more than that required for iron (Moore et al , 1999). Accordingly, the total energy consumption of the automobile has shifted from the use phase to the production phase.

Life Cycle Assessment (LCA) is an environmental management tool that can be applied to analyse material alternatives for automotive components from a life cycle and interdisciplinary perspective. Such an analysis will cover the whole life cycle of the automotive component, from the extraction and production of the raw materials, the foundry processing, the auto use phase and, finally, the end-of-life treatment of the component. The major strengths of LCA are to identify environmental burden shifting from one environmental compartment to another and to provide the necessary "big picture" perspective of a product system.

1.4.1 Problem Formulation

When it comes to saving weight, the material of choice always plays an important role. Substituting alternative materials such as aluminium alloys for conventional materials such as cast iron in automotive casting applications is an important strategy for reducing environmental burdens over the entire life cycle through weight reduction. Although lightweight materials can significantly reduce the overall fuel consumption of automobiles, the primary energy requirement for their production can be greater than that required for ferrous metals.

This leads to the question:

Which system of materials, aluminium or cast iron, reduces the total burdens on the environment most throughout the entire lifecycle of an automotive metal casting application?

1.4.2 Objectives of the Research

To deal with the problem, the main objective of this research work is to conduct a comparative Life Cycle Assessment study of an aluminium alloy casting and a cast iron casting. The aim of this comparison is to identify the best environmental proposition for a specific casting application such as an automotive suspension component. For this reason, a specialised LCA software tool (Boustead Model 4.4) will be used to compare and contrast the potential environmental impacts of the two alternative cast metal alloys.

To meet the main objective, the sub-goals are:

- Identify the implications of replacing primary aluminium and cast iron with secondary material for the material production phase.
- Determine at which stage of the life cycle phases significant environmental emissions occur.
- Examine the role of the Life Cycle Assessment methodology as a tool for identifying the environmental impacts of metal castings at various stages of their life cycle.

1.5 Research Methodology

The research work is divided into two areas, data collection and analysis. These two areas actually evolved side by side as further research was needed as the analysis produced questions, which could not be answered with the information previously gathered.

The data collection concentrated on the use of literature data rather than company-specific data. Data were collected for all pieces of information that might be relevant to the calculation of the life cycle inventories for both product systems. The task of data collection is not a linear process, but rather an iterative one involving identifying relevant and important flows or additional information. Sometimes many iterative loops are required to finalise these calculations.

Once the information had begun to be gathered, the initial analysis could start using the Boustead LCA Model. Literature searches were continued during this time to confirm or expand on the information already gathered

1.6 Structure of the Thesis

The thesis is subdivided into 7 chapters, which are structured as follows:

Chapter 1 (this chapter) provides an introduction to, and statement of, the research problem.

Chapter 2 covers the necessary theoretical background in metal casting to assist the reader in understanding the different casting materials and processes with a particular emphasis on the casting components used by the automotive industry.

Chapter 3 introduces the reader to the different environmental concepts and tools based on the life cycle thinking approach. The chapter also includes a review of the literature related to the Life Cycle Assessment methodology and its industrial application.

Chapter 4 considers in detail the research approach and methodology that was used to conduct the comparative LCA study. This methodology is based on the requirements of the ISO 14040 standards.

Chapter 5 reports the results of the comparative LCA study. The results are presented for both the initial study and the different life cycle scenarios.

Chapter 6 presents the necessary analysis and discussion of the results. The analysis identifies the most significant environmental issues and compares the alternative product systems in terms of potential environmental impacts.

Finally, Chapter 7 presents the research contributions and recommends some possible extensions for this work.

Chapter 2. Automotive Casting Materials and Processes

The metal casting process is the most direct and shortest route from the design to the production of various components. In fact, almost any metal that can be melted can also be cast and the design of castings can also be extremely flexible. This flexibility allows the foundry industry to produce simple or quite complex components, whether they are produced once as a prototype or thousands of times for use in a manufactured product. Among recognizable foundry products are the engine blocks, transmission housings and suspension parts of automobiles, structural and metal fittings for different appliances as well as pipes and valves.

This chapter provides an overview of the cast materials and processes with a particular emphasis on the components used by the automotive industry. Ferrous and non-ferrous castings will be covered in order to introduce the reader to the broader concept of metal casting. This chapter also provides an overview of the UK foundry industry and identifies the reasons for the current trend to develop lightweight castings in order to achieve weight reductions.

2.1 Casting Materials

Metal castings have the wide range of mechanical and physical properties of strength, stiffness and ductility, which are required for most applications. Only for special properties, such as low density, high thermal and electrical resistance or low wear rate, are plastics and polymers or ceramics and glasses considered for selection.

Materials for castings can be ferrous (iron and steel) or non-ferrous (e g aluminium, magnesium). About 75% of all cast products manufactured today are grey and ductile iron (Sustainable Industry, 1998, p.7). Table 1 shows the most common ferrous and non-ferrous casting metals.

Ferrous Castings	Grey Iron Castings
	Ductile Iron Castings
	Malleable Iron Castings
	Steel Castings
Non-Ferrous Castings	Aluminium Alloy Castings
	Magnesium Alloy Castings
	Copper Alloy Castings
	Zinc Die Castings

Table 1: Type of Casting Metals (SAE, 2001)

Traditionally, the majority of the automotive castings are produced from the following materials:

- Grey Iron
- Ductile iron
- Malleable iron
- Aluminium alloys

2.1.1 Grey Iron Castings

Grey iron is a cast iron in which the graphite is present in flake form. The graphite flakes provide many desirable properties such as excellent machinability, high thermal conductivity, vibration dampening properties and resistance to wear. Due to its comparatively low freezing temperature for a ferrous alloy, high fluidity and low shrinkage properties, it is more readily cast in complex shapes than other ferrous metals (Kalpakjan, 2001, p.307). Typical applications of grey iron for automotive castings include engine blocks, gear parts, camshafts, brake drums and clutch plates (SAE, 2001).

2.1.2 Ductile Iron Castings

Ductile iron, also known as spheroidal graphite iron, is cast iron in which the graphite is present as spheroids, instead of flakes as in grey iron. Ductile iron exhibits a linear stress-strain relation, a considerable range of yield strengths and, as its name implies, ductility. Ductile iron castings may be used in the as-cast condition or may be heat-treated (Kalpakjan, 2001, p 307). Typical applications of automotive ductile iron castings are crankshafts, suspension parts, camshafts, brake drums and clutch plates (SAE, 2001).

2.1.3 Malleable Iron Castings

Malleable iron is a cast iron in which the graphite is present as temper carbon nodules, instead of flakes as in grey iron or spheroids as in ductile iron. A wide range of mechanical properties can be obtained in malleable iron by controlling the matrix structure around the graphite. Typical applications of malleable iron for automotive castings include steering gear housings, mounting brackets, certain compressor crankshafts and transmission gears (SAE, 2001).

2.1.4 Aluminium Alloy Castings

Alloys with an aluminium base have a wide range of mechanical properties, mainly because of various hardening mechanisms and heat treatment that can be used with them. Therefore, there are two general types of automotive cast aluminium alloy: non-heat treatable and heat treatable. The non-heat treatable alloys are normally used in the as-cast condition, but may be annealed to relieve casting stresses or to reduce the possibility of distortion during machining. The heat treatable alloys usually are used in the heat-treated condition because of the increased strength resulting from the heat treatment. (SAE, 2001)

Aluminium alloy castings are normally used in non-structural automotive applications such as transmission cases, intake manifolds, pistons and cylinder heads. However, during recent years there has been a trend towards the use of aluminium alloy castings in structural automotive applications such as steering knuckles, brake drums and suspension parts.

2.2 Casting Processes

In general, metal castings are produced from molten metal that is poured and cooled in moulds. The metal casting industry encompasses ferrous foundries, non-ferrous foundries and die casting facilities. Foundries cast both ferrous and nonferrous metals, using primarily expendable moulds constructed using sand and patterns of wood, wax, foam, or other materials. Die-casting produces non-ferrous (primarily aluminum) castings under high pressure in permanent metal moulds. Metal casting involves five process stages (Beeley, 2001):

1) Pattern, mould and core preparation.

The casting process begins by developing a replica or "pattern" of the part that will be cast. The pattern is used to prepare a mould into which the metal will be poured. Additionally, the pattern is used to construct permanent or expendable moulds. Depending on the part being cast, foundries may also construct cores, which are inserted into the moulds prior to metal pouring to shape the interior of the casting.

2) Metal melting and pouring.

Scrap metal and/or metal ingots are melted in furnaces, transferred to holding furnaces, and poured into the die casting machines or foundry moulds Die casting machines inject metal into the permanent mould, where the part is formed, and eject a solidified casting. Foundries pour the metal into the moulds and transfer them onto the shop floor or into a cooling tunnel.

3) Knockout and sand handling

Foundries (but not die casters) must remove the castings by destroying the moulds. Foundries using sand moulds utilize vibrating grids or conveyors to shake the sand mould from the casting. The sand is then processed to remove lumps, metal, impurities, and fine particles. Much of the sand is reused on-site.

4) Fettling

All castings require some degree of cleaning and finishing in which excess metal is removed.

Metal casting processes vary in the type of metal poured, the type of mould used, and the degree of automation. Table 2 shows the classification of metal casting processes that could be used to produce automotive components.

Expendable Mould / Permanent Pattern Processes	• Green sand/Dry sand casting • Sodium silicate - CO_2 moulding • Shell casting • V – process • Eff – set process • Plaster mould • Ceramic mould • Shaw process • Expendable graphite moulding • Rubber mould casting
Expendable Mould / Expendable Pattern Processes	• Evaporative pattern casting • Investment casting
Permanent Mould Processes	• Gravity die casting • Pressure die casting • Squeeze casting • Slush casting • Centrifugal casting • Continuous casting • Electromagnetic casting

Table 2: Metal Casting Processes (Happian-Smith, 2001, p.79)

2.3 The UK Foundry Industry

The UK foundry industry comprises of over 600 companies varying in size and utilizing a wide range of production methods and degrees of automation. Currently production is in the region of 1.3 million tonnes split between several metal and alloy groups. As illustrated in Table 3, iron castings account for nearly 76% of all castings produced in the UK. These castings are used in a very wide variety of applications that include automotive, water distribution, fluid transmission, energy and aerospace industries.

Metal	Annual Tonnage	Percentage of Total (%)
Iron	968,200	76
Aluminium	169,300	13
Steel	96,800	8
Zinc	19,500	1.6
Copper	16,200	1.2
Magnesium	1,400	0.2

Table 3: Metals used in UK Casting Processes (Mass Balance, 2003, p 18)

The foundry industry in the UK has been in long-term decline. Since the late 1960's, production and employment in the British foundry sector has significantly reduced. The production of iron castings was about 4.5 million tonnes in the mid 1960's, reducing to 3 million tonnes in 1975 and then to 1 million tonnes in 1986. Since this time it has been stabilised at around 1 to 1.5 million tonnes annually. On the other hand, the non-ferrous casting market is benefiting from the trend in the transportation sector to lower the weight of cars to increase their fuel efficiency. Aluminium castings production has steadily increased from 80 thousand tonnes to 120 thousand tonnes per annum since the mid 1980's. (Mass Balance, 2003, p 19)

2.3.1 Environmental Overview of the UK Foundry Industry

As environmental standards have tightened since the 1970's, foundries have come under increased scrutiny by stakeholders at national, regional and local levels. Regulatory drivers, however, continue to be the main factor in industry efforts to improve their environmental performance. The UK foundry industry is governed by a variety of different environmental regulations and taxes with particularly relevant examples being the Landfill Tax and the Climate Change Levy.

Reducing the volume of wastes produced and increasing energy and other kinds of efficiency are important environmental and economic opportunities for UK foundry industry. Although the foundry industry is renowned for using recycled metal to produce new products, there is still a great deal of sand produced as waste, some wood/paper as well as ceramic materials, dust and slag for which reuse potential exists. These materials account for almost half a million tonnes of waste per annum (see Figure 1).

However, the major environmental pressure to the foundry industry today comes from the consumption of energy. The industry is a significant user of energy and, not surprisingly, melting and holding of metal is the major consumer of energy. It was estimated that the foundry industry consumed approximately 3.5 million MWh of energy in the year 2000. This produced 1.12 million tonnes of carbon dioxide, of which about 40% was produced directly by the foundry industry with the balance being output from electricity generation (Mass Balance, 2003, p 45). Whilst melting and holding account for the major part of consumption, between 20 and 50% (average 35%) of a foundry's energy consumption is related to 'services'. These services comprise motors and drives, compressed air, lighting, space heating etc. (Energy Saving, 1995)

The UK Foundry Mass Balance Project (Mass Balance, 2003) calculated that approximately 4.5 million tonnes of direct inputs were required to produce 1.3 million tonnes of castings. Figure 1 shows the total mass balance for the whole of the UK foundry sector in the year 2000.

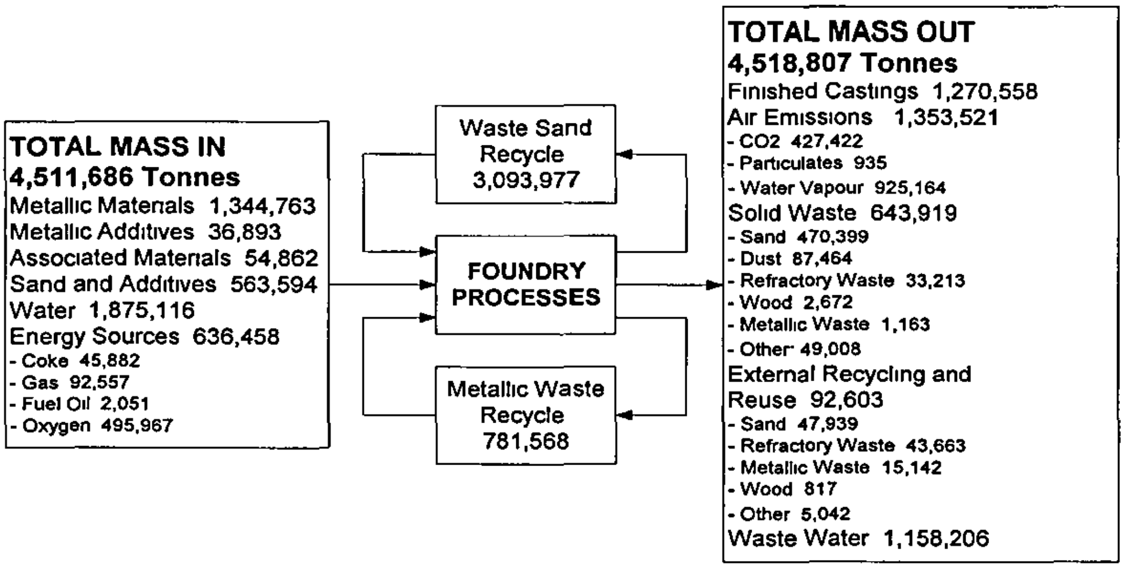


Figure 1: Overall Foundry Sector Mass Balance (Mass Balance, 2003)

2.3.2 Market Pressures

The UK foundry industry has been reshaped by a number of important trends over the past twenty years. However, the most important pressure on the industry is the demand to reduce the weight of castings. This trend comes directly from customers because reducing the weight reduces the cost and because a reduction in the weight of the final component reduces the energy required for moving it. The latter point is especially important in vehicles that consume large amounts of fuel over their entire life cycle. Successful efforts by foundries to meet such light weighting demands may not only benefit the foundry but can also provide a selling point for car manufacturers claiming lower fuel consumption and reduced emissions into the atmosphere. In a recent survey, 75% of the responding UK foundries reported that their customers are pressing hard for the weight of castings to be reduced. (Non-Ferrous Foundries, 1997, p 16)

2.4 Metal Castings for the Automotive Industry

The automotive industry uses a wide range of materials. Among the metals, steel and iron lead the way followed by aluminium. Steel makes up 55% of an average vehicle, followed by iron at 13%, and aluminum at 6% (Bulkley, 1997).

The paradox of removing weight to reduce the fuel consumption of automobiles while designing higher performance vehicles is a major challenge confronting the automotive industry of today. In many cases, cast metal components provide the flexibility needed to meet this difficult challenge. Castings offer improved quality, reliability and durability at a lower cost as well as design for manufacturability. In addition, during the casting process, metal can be treated to achieve the desired characteristics of costlier materials at a lower cost than other manufacturing methods.

2.4.1 Automotive Casting Applications

Automotive casting applications can be classified in two categories, structural castings and non-structural castings. Table 4 shows the most common automotive casting applications and their classification.

Structural Automotive Applications	Non-Structural Automotive Applications
• Steering wheels • Crankshafts • Engine blocks • Suspension parts • Steering knuckles • Gear parts	• Transmissions cases • Transfer cases • Valve/cam covers • Intake manifolds • Electric motor/alternator housings etc.

Table 4: Classification of Automotive Casting Applications

In structural automotive applications ductility as well as adequate tensile and fatigue properties are essential attributes of the cast metal product. On the other hand, in non-structural automotive applications ductility is generally not an important mechanical attribute but the ability to be cast to close dimensional tolerances is usually essential. In some applications, bolt load retention and creep resistance are also very important.

2.4.2 Automotive Light Weighting Initiatives

Since the stimulus provided by the energy crisis of the 1970's, there was a 26% vehicle weight reduction between 1976 and 1986. However, in the late 1980's, improved vehicle performance, driving comfort, increased safety and easier maintenance led to a vehicle weight increase of 8% between 1986 and 1992. However, current environmental concerns have returned weight reduction to the fore because it offers benefits to consumers and society as a whole. (Bulkley et al., 1997)

A number of joint European and North American automobile industry research projects and environmental initiatives are attempting to reduce vehicle weight and, consequently, improve fuel economy. EUCAR, the European automotive industry's research and development body under the umbrella of the European Automobile Manufacturers Association (AECA), is currently working with lightweight materials for vehicles. Environmental agreements with automobile manufacturers are central to the European Union's strategy for reducing CO_2 emissions from new passenger cars. In 1999, the European Commission negotiated a voluntary agreement with ACEA committing automobile manufacturers to reduce the average vehicle emission of CO_2 by 25% by 2008 (Commission Recommendation 99/125/EC).

Vehicle mass reduction using lightweight materials is one aim of the American Partnership for a New Generation of Vehicles (PNGV). This cooperative research and development programme is between the federal US government and several research institutes, automotive suppliers, universities and the United States Council for Automotive Research (USCAR), whose members are the "big three" US automotive companies, Ford, DaimlerChrysler and General Motors. A principal objective is a 40% vehicle body weight reduction by 2004 (Partnership for a New Generation of Vehicles, 2003).

Two approaches to achieve vehicle weight reduction targets are: automotive design and materials selection. The former includes improved aerodynamic design and reduced rolling resistance. For materials selection, the use of lightweight metals and their alloys is the dominant approach.

Replacing ferrous components by those manufactured from lighter metals such as aluminium alloys can substantially reduce vehicle weight. Aluminium offers an ideal engineering solution since its density is one-third that of steel and it satisfies torsion and stiffness requirements. Consequently, aluminium use in passenger cars has grown steadily. Between 1980 and 1994, the aluminium content of the automobile increased by 40% and currently is growing by 4% annually (European Aluminium Association, 2003). However, aluminium is about five times more expensive than conventional ferrous automotive materials (Roth et al, 2001). Additionally, the primary energy requirement for the production of aluminium is about ten times that for iron, making aluminium very energy intensive (Moore et al., 1999).

Concurrent with the development of lighter materials there has been continual improvement in the properties of ferrous materials. The International Iron and Steel Institute (IISI) claims vehicle weight reductions of up to 40% with a "holistic" approach to design using high strength steel (ULSAB- Advanced Vehicle Concepts, 2003). The world steel industry has commissioned environmentally focused initiatives offering lightweight steel solutions to the challenges facing automakers. ULSAB-AVC has already achieved the stringent EUCAR and PNGV targets for fuel efficiency and vehicle weight reduction (Peterson, 2002).

Finally, it should be noted that economic considerations and recycling issues play an important role in the material selection process and often limit the application of the new lighter materials in the automotive sector.

2.4.3 Current Trends in Automotive Casting Applications

In the past, the automotive industry generally has regarded castings as commodities. Metal castings have been organised and purchased by metal type or manufacturing method such as aluminium castings or die-castings. Perceiving castings in this manner underestimates the complex engineering solutions that can be achieved through excellent casting design. However, it appears that this paradigm is slowly changing

The new trend in the automotive industry is to take a system focus vs. a component focus and look at manufacturing system functions vs. the component attributes. In other words, to replace the current *"commodity"* approach with a *"functional"* one. According to this new concept, the material or manufacturing method does not matter, as long as all functional requirements are met. Therefore, castings are currently being organised into functional groups such as engine block applications or suspension system applications (Foti, 2000). Cast metal for automotive applications is chosen with application in mind, not just material type and production costs.

In addition, the *"functional"* approach has forced vehicle manufacturers to require from their metal casting suppliers not only manufacturing but also engineering services, system responsibility and modular assembly. Automotive casters will be expected to offer components that exhibit the greatest performance characteristics at the lowest cost as well as a complete complement of product alternatives. (Foti, 2000)

Chapter 3. Life Cycle-Based Concepts and Tools

Any environmental, economic, or social assessment method for products and services has to take into account the full life cycle from raw material extraction through production, use and recycling to waste disposal. In other words, a systems approach has to be taken into consideration. Only in this way can trade-offs be recognized and avoided. Life cycle thinking is the requirement of any environmental assessment and the key element in achieving movement towards sustainable development.

Life cycle approaches avoid problem shifting from one life cycle stage to another, from one geographic area to another and from one environmental medium to another. It does not make any sense at all to improve one part of the system in one country, in one step of the product life cycle, or in one environmental section, if this improvement has negative consequences for other parts of the system, which may outweigh the advantages achieved. Life Cycle Assessment (LCA) is such an analytical life cycle-based tool that provides an expanded view of environmental management in order to look at the entire system from "cradle to grave".

This chapter introduces the reader to environmental concepts and tools based on the life cycle thinking approach. In particular, the chapter provides a description of Life Cycle Assessment using the International Organization for Standardization (ISO) technical framework, which divides the entire LCA procedure into four distinct phases. The chapter also presents industrial applications of LCA with a particular emphasis on how LCA has been used by the automotive industry as a tool to justify environmental superiority of products, materials or processes.

3.1 Concepts and Tools

In recent decades, concerns about the environment and, more recently, sustainability have generated new ideas, policies and technologies, tools, and methodologies. These concept and tools are becoming increasingly important for forward-thinking nations and corporations in order to achieve the broader concept of sustainable development. The sustainable development concept actually means that a balance between industrial development, environment and social justice is needed in further economic development for the whole society.

Figure 2 provides an overview of the concepts (outer circle) and tools (inner circle), which are available in the international environmental debate to support sustainable development. It should be mentioned, that many of these concepts and tools have common characteristics and even overlap each other.

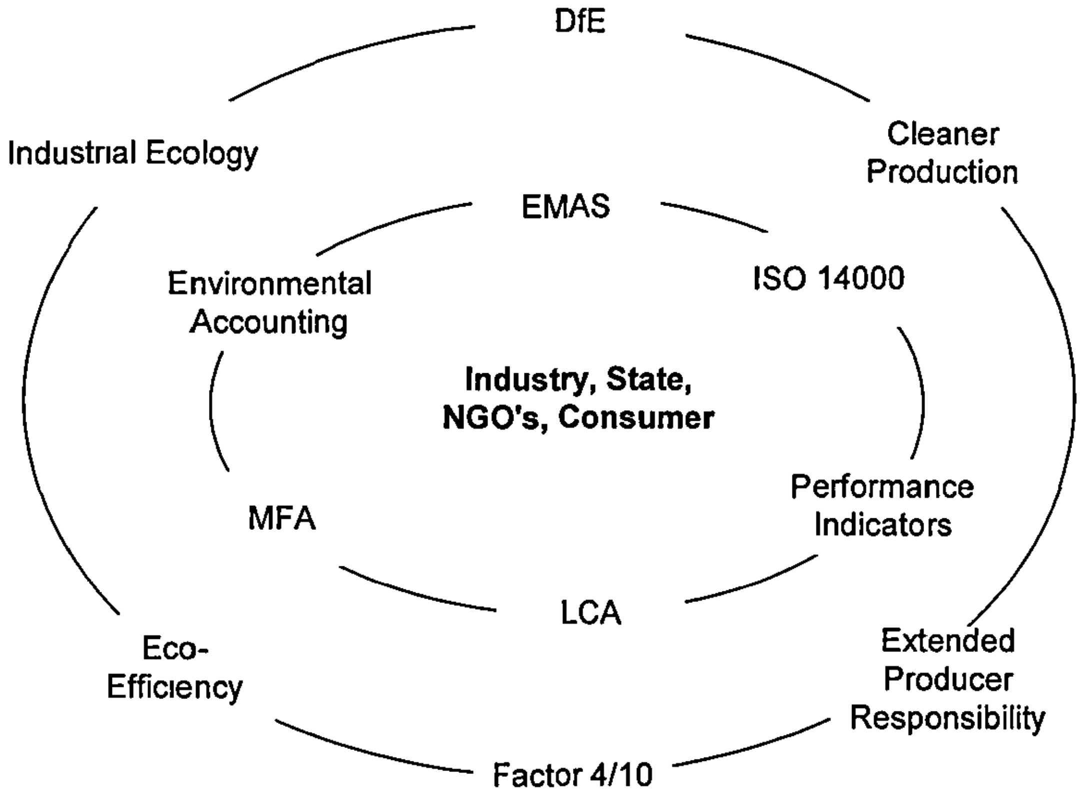


Figure 2: Concepts (outer circle) and Tools (inner circle) for Sustainable Development

International trends are demonstrating that some of these concepts and tools such as Industrial Ecology, Design for Environment (DfE) and Life Cycle Assessment (LCA) are here to stay. Industrial ecology is currently identified as a broad umbrella of concepts rather than a unified theoretical construct. As such, it is described and presented in different ways by different authors. In general, the concept *"requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them"* (Graedel, Allenby, 2003, p.17). The idea is that no firm exists in a vacuum but is linked to thousands of other transactions and activities and to their environmental impacts. On the other hand, Factor 4/10 and DfE have a more narrow meaning. Factor 4/10 proposed a factor of 10, or the more moderate 4, as a general goal for the increase of resource productivity of industrialised counties within the following 50 years in order to cut in half the global resource requirements. While, the idea behind DfE is to ensure that all relevant environmental considerations and constrains are integrated into a firm's product design process.

Many closely related tools, all based on a cradle to grave approach, have also been developed and used to analyse products and their interactions with the environment. Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) are such representative tools. The major difference between them is that LCA is an analytical tool for specifying product chains while MFA is used for specifying material or even substance chains.

In recent years, LCA has become as much a way of thinking as a specific tool or methodology. However, although it can be seen as a concept, the term LCA has stricter application as a specific and internationally standardised methodology for assessing environmental burdens from product systems.

3.2 Life Cycle Assessment

The generally recognised term for environmental assessment of products is Life Cycle Assessment or LCA in abbreviation. In fact, LCA is an environmental assessment methodology that considers all product environmental burdens over the entire life cycle, from the material production to part manufacture, product assembly, operation, servicing, maintenance, and end-of-life disposition. For this reason, LCA is sometimes referred to as "cradle-to-grave" assessment because it provides the required wider perspective of a product system. It should be mentioned that the term "product system" is taken in its broader sense, including the product itself as well as processes and services associated with the product. For instance, in a comparative LCA study it is not the products themselves that form the basis for the comparison, but the function provided by these products.

The roots of LCA go back to the early 1960's when cradle to grave industrial energy analyses were routinely conducted. They were called "Research and Environmental Profile Analyses" (REPA) and focused primarily on energy consumption, resource consumption and waste generation. However, interest in life cycle assessment intensified during the late 1980's when the technical framework for LCA was first developed. Since then a growing number of different and increasingly complex products and systems have been assessed using the LCA methodology. (Alting et al., 1997, p 27)

Currently, the main drivers of LCA activity in European companies are end-of-life waste management regulations and cross-sectoral market competition (ENDS, 1999). In particular during the 1980s and 1990s, demand for many products was threatened by new regulations regarding the management of end-of-life wastes. Firms producing these products have sought to influence the regulatory process and the impacts of these regulations in the market by using LCA-based claims to support their position LCA-based claims have also been extensively used in cross-sectoral competition between substitute commodity products, such as steel versus aluminium in the car industry (ENDS, 2003).

3.2.1 Life Cycle Assessment Framework

In September 1996, the International Organization for Standardization (ISO) initiated the ISO 14000 series of environmental management system standards. These are a series of standards that deal with the components of an effective environmental management system along with guidelines for auditing, eco labelling, environmental performance evaluation and LCA. For our purposes, the ISO 14040 standards of LCA are of most interest. These standards were developed in 1997 and attempt to provide consistency among LCA efforts and ensure that all LCA practitioners are using similar tools and techniques (ISO 14040, 1997).

In accordance with the current terminology of the ISO 14040 standards, LCA is structured within a framework, which divides the entire LCA procedure into four distinct phases:

- Goal and scope definition
- Life Cycle Inventory analysis
- Life Cycle Impact assessment
- Life Cycle Interpretation

Figure 3 illustrates the Life Cycle Assessment framework.

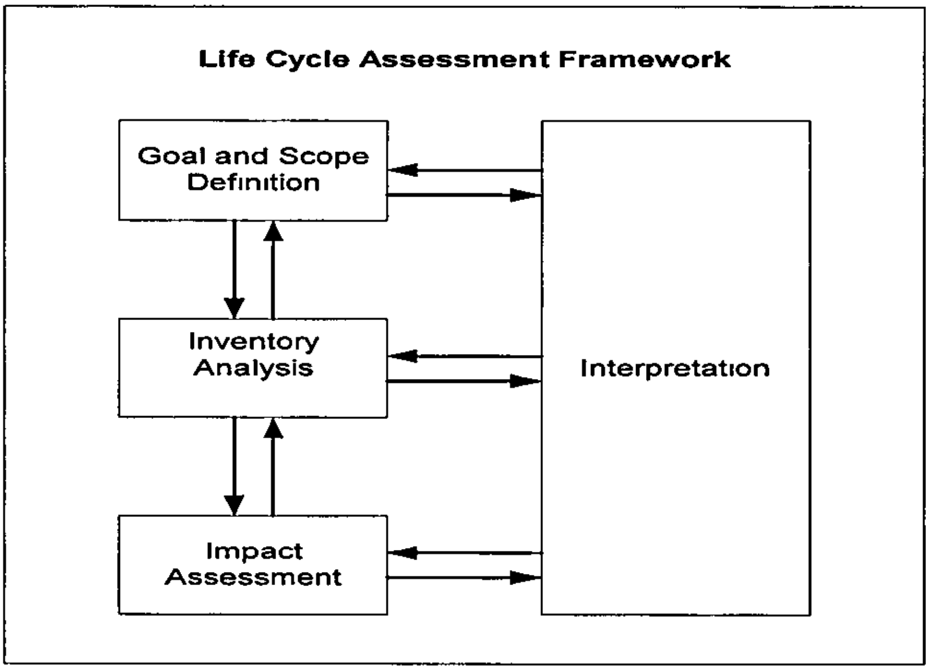


Figure 3: LCA Framework (ISO 14040, 1997)

3.2.1.1 Goal and scope definition

The goal and scope definition is the phase in which the initial choices which determine the working plan of the entire LCA study are made. In this first phase the purpose of the LCA study is described. This description includes the intended application and audience, and the reasons for carrying out the LCA study. Furthermore, the scope of the study is described. This includes describing the function of the system investigated, the functional unit, and the boundaries of the product system.

3.2.1.2 Inventory analysis

In the inventory analysis phase the product system of the LCA study is defined. Defining the product system includes designing the flow diagrams with unit operations, collecting the data for each of these operations, and completing the final calculations. Mass flows and environmental inputs and outputs associated with the functional unit are calculated, interpreted and presented.

3.2.1.3 Impact assessment

In the impact assessment phase, the environmental impacts are evaluated. The set of results from the inventory analysis phase are further processed and interpreted in terms of potential environmental impacts. The impact assessment phase can be divided into three sub-phases: selection of impact categories and category indicators, classification and characterization. The first sub-phase identifies the environmental impact categories. For each impact category, the category indicator is selected. In the classification, the parameters used in the inventory analysis are sorted into the environmental impact categories. Finally, in the characterization sub-phase, the potential contribution of the environmental burdens to each impact category is calculated. In addition, according to the ISO standards, there are the optional steps of normalization, grouping, weighting and data quality analysis that can be followed depending on the goal and scope of the LCA study.

3.2.1.4 Interpretation

Interpretation is the phase in which the results from the inventory analysis and the impact assessment are evaluated and analysed from a perspective consistent with the defined goal and scope of the LCA study. The purpose of this phase is to reach relevant conclusions and recommendations for the LCA study. The conclusions of the LCA study should be compared to the goals defined at the beginning of the study. If the goals are not fulfilled, the LCA may have to be improved, or the goals may have to be adjusted

In general, an LCA study is an iterative process. For instance, the impact assessment phase can increase the knowledge of what environmental inputs and outputs are important. This knowledge can be used in the collection of better data for an improved inventory analysis.

3.2.3 LCA as a Tool to Justify Environmental Superiority

Life Cycle Assessment (LCA) is becoming accepted as the method for determining the environmental performance of automobiles over their entire life cycle. This is expressed by LCA studies and projects to examine the life cycle impacts of different concepts, processes and materials; determine life cycle costs; and improve automobile design.

These LCA studies can be grouped into different categories according to focus:

- Product-related LCA studies
- Production-related LCA studies
- Concept-related LCA studies
- Full Vehicle LCA studies

Product-related LCA studies are the most common studies and mainly focus on material selection. Several publications such as Saur et al (2000), Gibson (2000) and Costic et al (1998) present LCA studies in which alternative materials were compared to identify the best environmental proposition for a specific automotive component. Jenssen et al (2000) performed LCA to compare aluminium and steel in the design of the new Opel Corsa bumper carrier. The study focused on air emissions, specifically global warming potential (GWP), and concluded that aluminium causes lower greenhouse gas emissions when used for this specific application.

Production-related LCA studies are less common and mainly focus on manufacturing process and end-of-life process selection. Stephens et al (2001) performed an LCA study for three aluminium casting processes: lost foam, semi-permanent mould and precision sand casting. They concluded that lost foam casting of automotive aluminium heads and blocks has less environmental impacts than the alternatives.

Concept-related studies have focused on innovative automotive technologies such as studies in which conventional vehicles are compared with new concepts such as electric and hybrid vehicles (Couslon, 2000). Aoki et al (2001) performed an LCA comparing three types of vehicles: the aluminium-bodied hybrid Honda Insight, a simulated steel-bodied Honda Insight and a conventional gasoline vehicle. The LCA study concluded that the hybrid vehicle emitted the lowest CO_2 emissions.

Finally, a number of LCA studies have been conducted on the full vehicle product system. Such studies are intended to estimate the holistic impact of the vehicle product system on the environment. In fact, these studies are Life Cycle Inventory (LCI) studies, the quantitative stage of LCA, since it is too costly and time consuming to conduct such a full LCA. Sullivan et al (2001) conducted a review of nine published full vehicle LCI studies and concluded that the use phase is dominant. The use phase is responsible for 60-80% of the life cycle energy consumption and CO_2 emissions. However, for solid waste, the material production phase is dominant and responsible for 60-80% of the total life cycle burdens.

Several automotive companies have applied LCA to the early stages of product development in order to estimate the environmental effects of new automotive concepts or technologies. Mercedes-Benz has applied LCA to over 100 product-related studies as well as several for full vehicles as part of its development process (Finkbeiner, 2001). Volvo Car Corporation has, since 1998, published environmental product declarations (EPD) for each new car model that present environmental information for consumers on the cars' whole life cycle using information based on individual LCA studies for each model (Dahlqvist, 2001).

LCA methodology has also been applied to judge products from an interdisciplinary perspective. For example, BMW Group conducted a LCA study of a side-frame made of conventional steel or Carbon-Fibre-Reinforced-polymer (CFRP) and concluded that CFRP was the best environmental proposition. However, CFRP structural components are currently not regarded as economically recyclable which limits their application (Fried, 2002).

3.3 Critical Summary

In the foregoing chapters, it has been shown that Life Cycle Assessment is an emerging scientific instrument that can be used to evaluate the environmental performance of a product system and not just the products over their entire lifetime. Since its inception, LCA has undergone continuous change, ending with the recently completed ISO 14040 standards outlining a standardised approach.

Life Cycle Assessment has been applied in many ways both internally (within an organisation) and externally (by the public and private sectors). However, product comparison based on LCA claims has received the most attention and has been used to compare the environmental profiles of alternative products, processes, materials or activities and to support marketing claims.

Vehicle weight reduction via material substitution is such a claim that has been used to achieve fuel economy improvements and it is still a major challenge for the automotive industry of today. In many cases, cast metal components provide the flexibility needed to meet this difficult challenge. To explore the validity of this claim, LCA could be used to assess whether there are any important trade-offs associated with material substitution.

However, past experience has shown that many problems and difficulties are associated with the application of the LCA methodology. The amount of data and the time required can make them very expensive and time consuming and it is not always easy to obtain all the necessary data. Further, it is hard to properly define the system boundaries and appropriately allocate inputs and outputs between product systems and different life cycle stages. It is also often very difficult to assess the quality of data collected because of the complexity of certain environmental impacts. Regardless of the current limitations, LCA is a promising tool to identify and compare the environmental burden of product systems as long as a standardised framework is used.

Chapter 4. Life Cycle Assessment Methodology

The research approach compares the environmental life cycle inventory of automotive casting components made from aluminium alloy with components made from conventional cast iron using life cycle assessment.

This chapter presents the methodology that was used to conduct the comparative LCA study. The study was developed in accordance with the requirements of the ISO 14040 standards which were presented in Chapter 3.2.1.

As previously mentioned, the ISO 14040 standards divide the entire LCA procedure into four phases (see Figure 3):

- Goal and scope definition
- Life Cycle Inventory analysis
- Life Cycle Impact assessment
- Life Cycle Interpretation

4.1 Goal and Scope Definition

The goal of the LCA study is to assess the environmental performance of two automotive casting components; an aluminium alloy component and a cast iron component. The environmental aspects of the two alternatives were to be analysed within a comparative life cycle assessment. The main objective of this comparative LCA was to quantify energy and other environmental trade-offs associated with each alternative and, consequently, identify the best environmental proposition for a specific automotive application. However, the study was focused on air emissions and, more specifically, global warming potential as well as energy consumption associated with the different life stages of both the aluminium alloy and the cast iron product systems. The intended application of the study was to increase the knowledge of the potential environmental impacts associated with the life cycle of two alternative components.

4.1.1 Function and Functional Unit

An automotive suspension arm was selected as the functional unit for the LCA study. The suspension arm is one of the major components of the automotive suspension system. The function of the suspension arm is to hold the position of the whole suspension system in relation to the vehicle in order to provide steering stability. In fact, the weight of the vehicle is transmitted through the spring to the suspension arm and then to the ball joint of the automotive suspension system. A picture of an aluminium alloy suspension arm is presented in Figure 4.

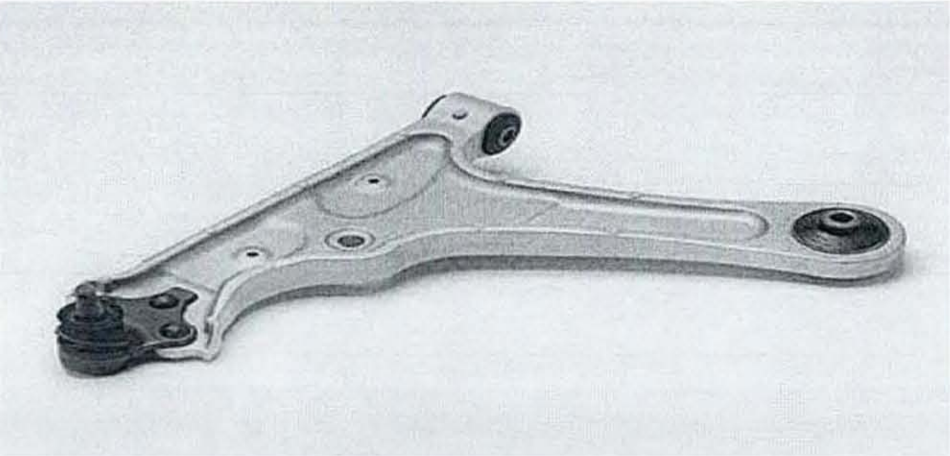


Figure 4: Aluminium Alloy Suspension Arm

In comparative LCA studies it is considered essential to use the same functional unit in order to obtain reliable and comparable results. Therefore, the two suspension arms have identical technical specifications. This ensures that the functional unit is well defined and that the two alternatives are comparable.

The function of the cast iron suspension arm is exactly the same as the aluminium component. The only difference between the two alternatives is the lower weight of the aluminium alloy due to its low density that is almost 1/3 of the cast iron (Kalpakjan, 2001, p.91). Past experience has shown that the weight of automotive suspension components can be reduced by about 30% when converting from cast iron to aluminium alloys (Lessiter, 2000). Table 5 shows the materials and weights of the two alternative automotive suspension arms.

Material	Weight (kg)
Cast Iron	5
Aluminium Alloy	3.5

Table 5: Material and Weight of Suspension Arms

4.1.2 Initial System Boundaries

An LCA should include all processes contributing significantly to the environmental impacts of the product systems investigated. In a comparative LCA, it is particularly important to include all processes where the difference between the product systems is significant. In general, the life cycle of the two alternative product systems consist of the following five life cycle stages:

1) Material production (primary and secondary)
2) Foundry process
3) Manufacturing and assembly
4) Auto use phase
5) End-of-life management

Figure 5 illustrates the initial system boundaries of an automotive suspension arm.

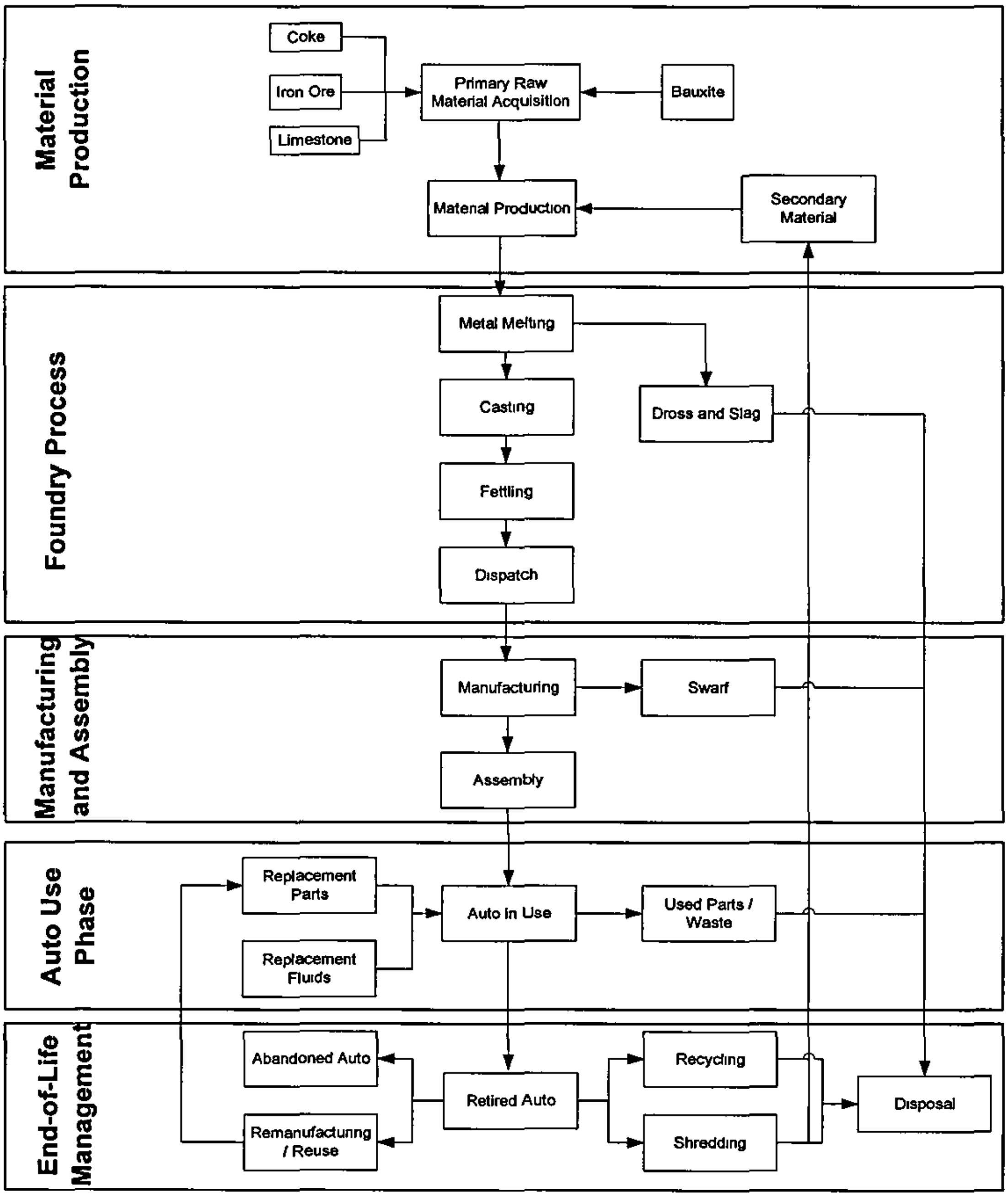


Figure 5: Life Cycle Stages of an Automotive Suspension Arm

4.1.3 Limitations of the LCA study

An initial limitation of the current LCA study is that the data collection only included literature sources and commercial databases. Although industrial companies have been asked to provide data for different industrial processes, it was not possible to collect and present the data at the time of this report.

This study has relied particularly on the Boustead Model database to construct life cycle inventories for the two alternative components. Life cycle data for many materials were obtained directly from the Boustead database.

Finally, data collection efforts have been focused on processes or even life cycle stages where preliminary calculations or earlier experience indicated that the difference in environmental impacts could be significant.

4.1.4 Key Assumptions

Although LCA aims to be a science-based process, it always involves a number of technical assumptions and value choices. Therefore, it is considered quite important to clearly state these assumptions and make them as transparent as possible in the LCA study report.

The current study involves assumptions related to:

- Weight of the functional unit
- Percentage of virgin and secondary materials in the material production phase
- Exclusion of minor life cycle stages from LCI calculations

Weight of the Functional Unit

As mentioned previously, the LCA study assumes that the cast iron suspension arm weights 5 kg while the weight of the identical aluminium alloy component is 3.5 kg. This assumption based on past experiences and studies which showed that a weight reduction of 30% for the aluminium substitution was reasonable.

It should also be mentioned that this particular component was chosen only as a model case study. One reason this component was selected is that several automotive manufacturers have considered substituting traditional material such as cast iron with lighter material such as aluminium in structural automotive applications like suspension components.

Percentage of Virgin and Secondary Materials

The initial LCA study (base case scenario) assumed that 100% virgin material was used in order to produce the two alternative suspension components. However, it should be noted that iron and aluminium castings used in automotive components typically contain 60 to 70% of secondary material (Green et. al., 2000).

To accommodate this, the LCA study will examine four different life cycle scenarios in a sensitivity analysis. These scenarios will calculate the replacement of primary material by secondary sources resulting from recycling of metal scrap. The four life cycle scenarios are shown in Table 6.

Life Cycle Scenarios	Percentage of Virgin and Secondary Material (%)
1st Scenario	75% Virgin Material – 25% Secondary Material
2nd Scenario	50% Virgin Material – 50% Secondary Material
3rd Scenario	25% Virgin Material – 75% Secondary Material
4th Scenario	0% Virgin Material – 100% Secondary Material

Table 6: Different Life Cycle Scenarios

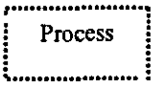
Exclusion of Minor Life Cycle Stages from LCI Calculations

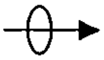
As already mentioned, the LCA study has been focused on processes or even life cycle stages where preliminary calculations or earlier experience indicate that the difference in potential environmental impacts can be significant between the two alternative choices. For example, earlier studies have shown that the primary energy requirement for the production of aluminium is ten times more than that required for iron. This results in a considerable difference in potential environmental impacts in the material production phase.

In this context, the LCA study assumes that the manufacturing and assembly and the end-of-life management phases have almost identical industrial processes for both aluminium and cast iron product systems and, consequently, discharge almost the same amount of pollution. As a result, it was decided that these two life cycle stages be excluded from the calculations of the life cycle inventory within this study.

4.2 Life Cycle Inventory Analysis

A Life Cycle Inventory (LCI) Analysis comprises the second stage of the LCA study. This stage involves compilation and quantification of inputs and outputs, of the given product system throughout its life cycle. The inputs are economic inputs of all sorts (e g. chemicals or fuels). Outputs are the processed products or materials and all emissions of substances to the environment. Such input /output data will be referred to as LCI data in this report. Furthermore, the initial system boundaries of the product system will be further analysed. Every flow that crosses the boundary between the product system and the environment will be explicitly defined. The life cycle stages of the product system as well as all the unit operations will be modelled using specific process flow diagrams.

In the flow diagrams, processes with dotted lines represent processes for which we have currently no data. For example: 

In addition, an arrow through an oval represents transports between processes and life cycle stages. For example: 

The calculations for the LCI phase were conducted with the aid of the LCA software tool Boustead 4.4 Model. The LCI results for both the base case and the alternative life cycle scenarios can be found in Appendices I to X.

4.2.1 Material Production

The material production phase comprises the acquisition of both virgin and secondary raw materials and their refinement to make constituent materials that comprise a product.

LCI data on energy consumption and air, water and solid waste emissions for both product systems were taken directly from the Boustead Model database.

Aluminium Alloy Product System

In the primary aluminium production process, alumina is first produced chemically from bauxite, which is extracted from bauxite mines. Then aluminium metal is produced from alumina by an electrolytic reduction process. Finally, molten metal is transferred to holding furnaces, where it is refined and mixed with metal additives to produce aluminium alloy ingots. The entire life cycle of the primary aluminium production also includes a number of other production processes such as bauxite mining, NaOH production, petrol coke production as well as transportation between these processes.

Secondary aluminium production consists of new and old scrap material. Most new scrap aluminium comes directly from the fabricators while old scrap comes via a complex network of aluminium refiners and metal merchants. Usually, secondary aluminium refiners convert most of their scrap materials into foundry ingots that go directly into the casthouses.

Primary aluminium ingot is produced in a three-stage process as illustrated by the flow diagram in Figure 6 while secondary aluminium comes from old and new scrap material

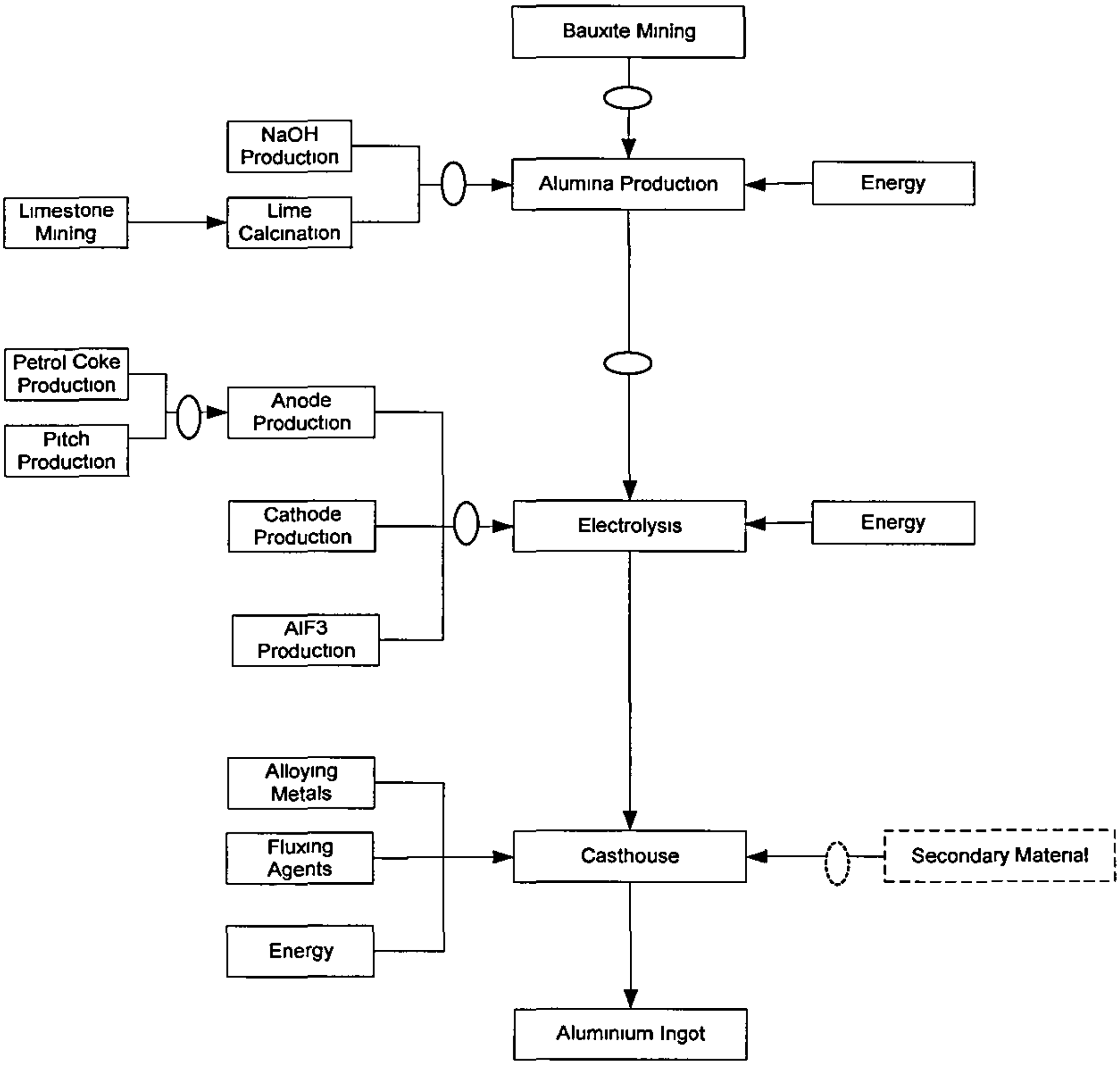


Figure 6: Aluminium Material Production Process Flow Diagram

Cast Iron Product System

The production of iron is a two-stage process. The first is the mining and preparation of iron ore, limestone and coal. Additionally, coal is dumped into large ovens where it is heated to up to 1315 ^{0}C, which removes most of coal's gases and converts it to coke. Gases generated during the conversion of coal to coke are used as fuel for other operations.

Then the three raw materials are carried to the top of the blast furnace and dumped into it where the mixture is melted in a reaction at 1650 ^{0}C. The molten metal accumulates at the bottom of the blast furnace, while slag floats over the molten metal, and is subsequently removed and later used in making cement, fertilizers, glass, building materials and road ballast. The molten metal at this stage is called pig iron or simply hot metal.

Figure 7 shows the flow diagram of the iron production process.

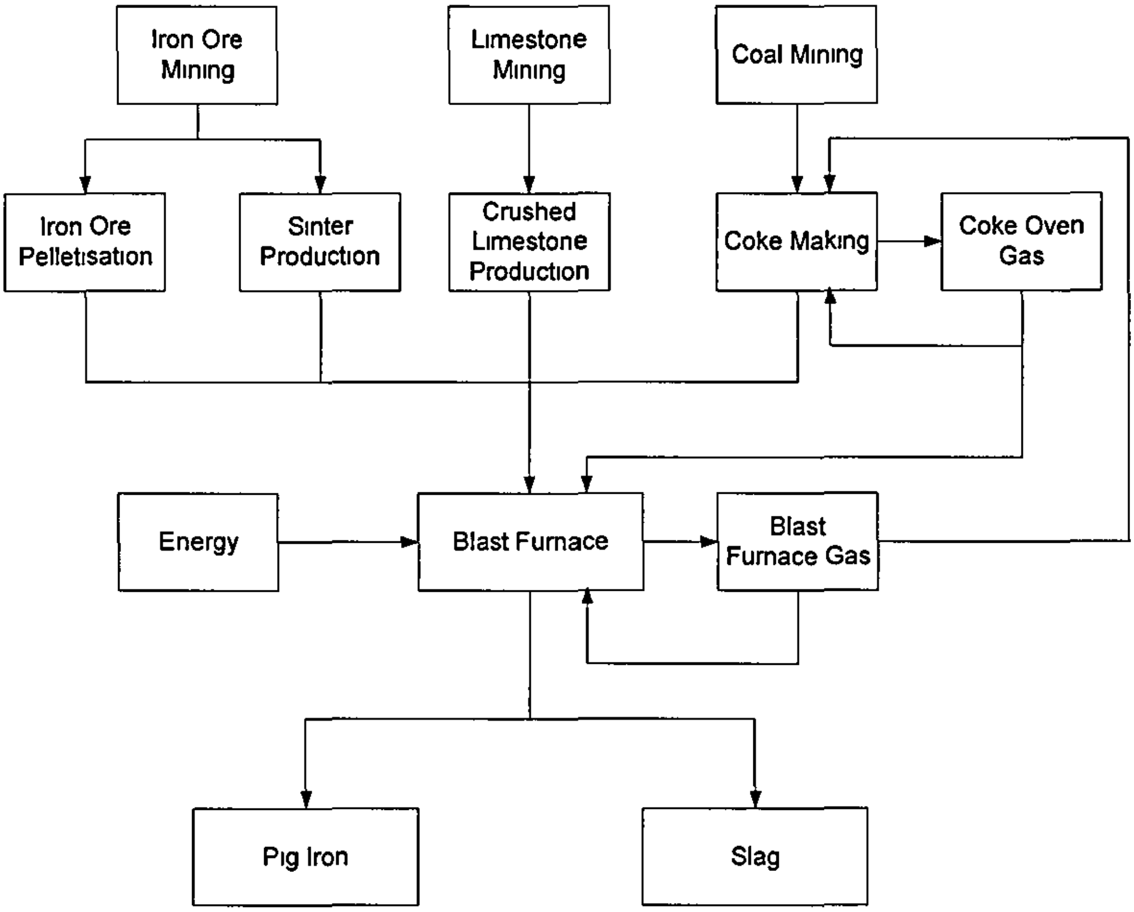


Figure 7: Cast Iron Material Production Process Flow Diagram

4.2.2 Foundry Process

In general, this life cycle stage includes the following steps: melting of raw materials, blending with molten materials or with additional alloying materials, fettling and dispatch of the finished casting.

LCI data for the foundry process of both aluminum alloy and cast iron castings were taken from a specific source (Mass Balance, 2003). However, mainly average figures concerning the energy consumption of the foundry process were obtainable and available for use.

Aluminium Alloy Product System

The LCA study assumes that the cast aluminium suspension arm is produced using a precision sand casting process. The precision sand casting process comprises the operations of mould and core making, melting and pouring, heat transfer, shake out and, finally, finishing.

A flow diagram of the foundry production process is shown in Figure 8.

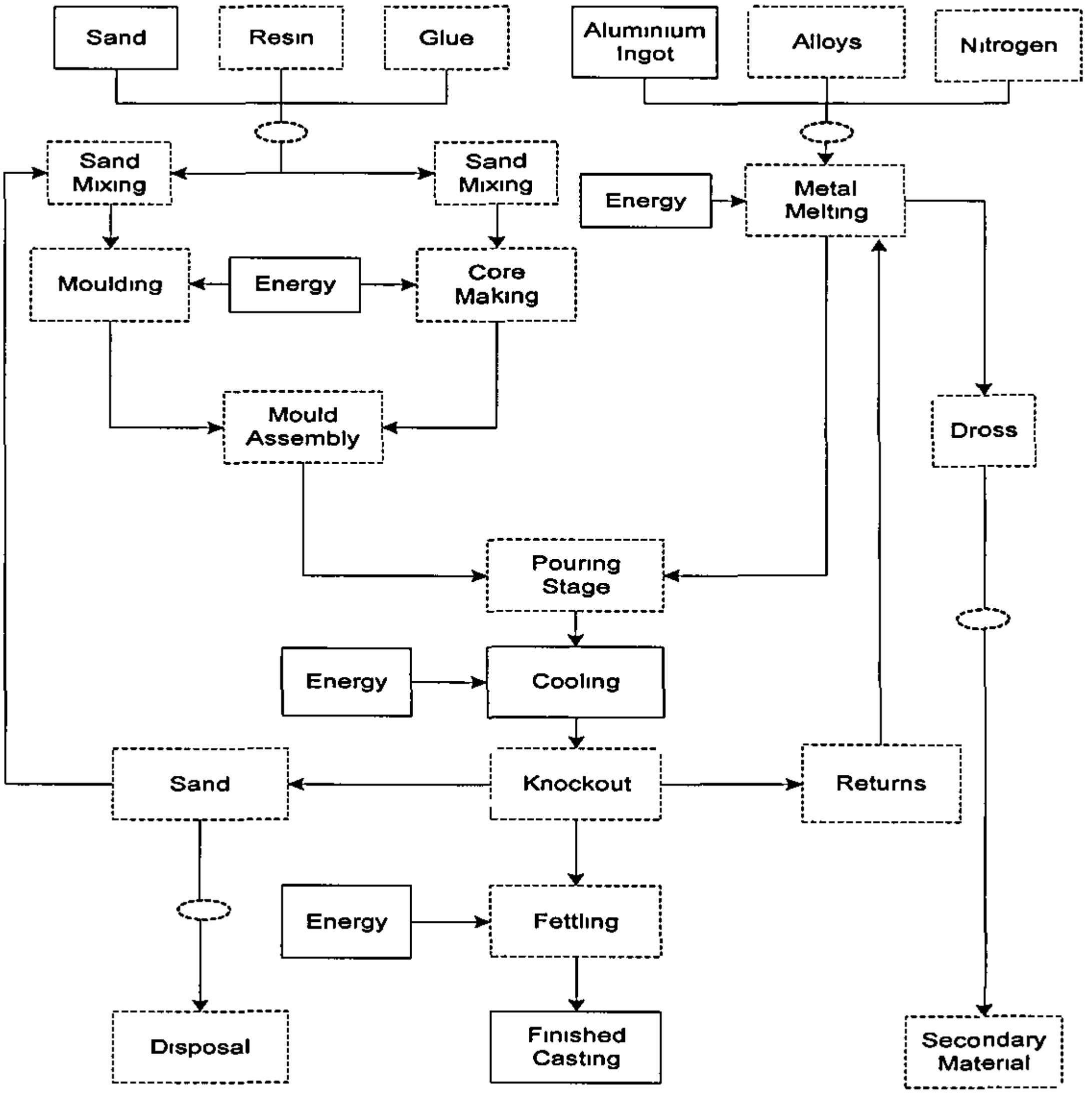


Figure 8: Aluminium Foundry Process Flow Diagram

Cast Iron Product System

The study assumes that the cast iron suspension arm is produced using a green sand casting process.

A flow diagram of the foundry production process is shown in Figure 9.

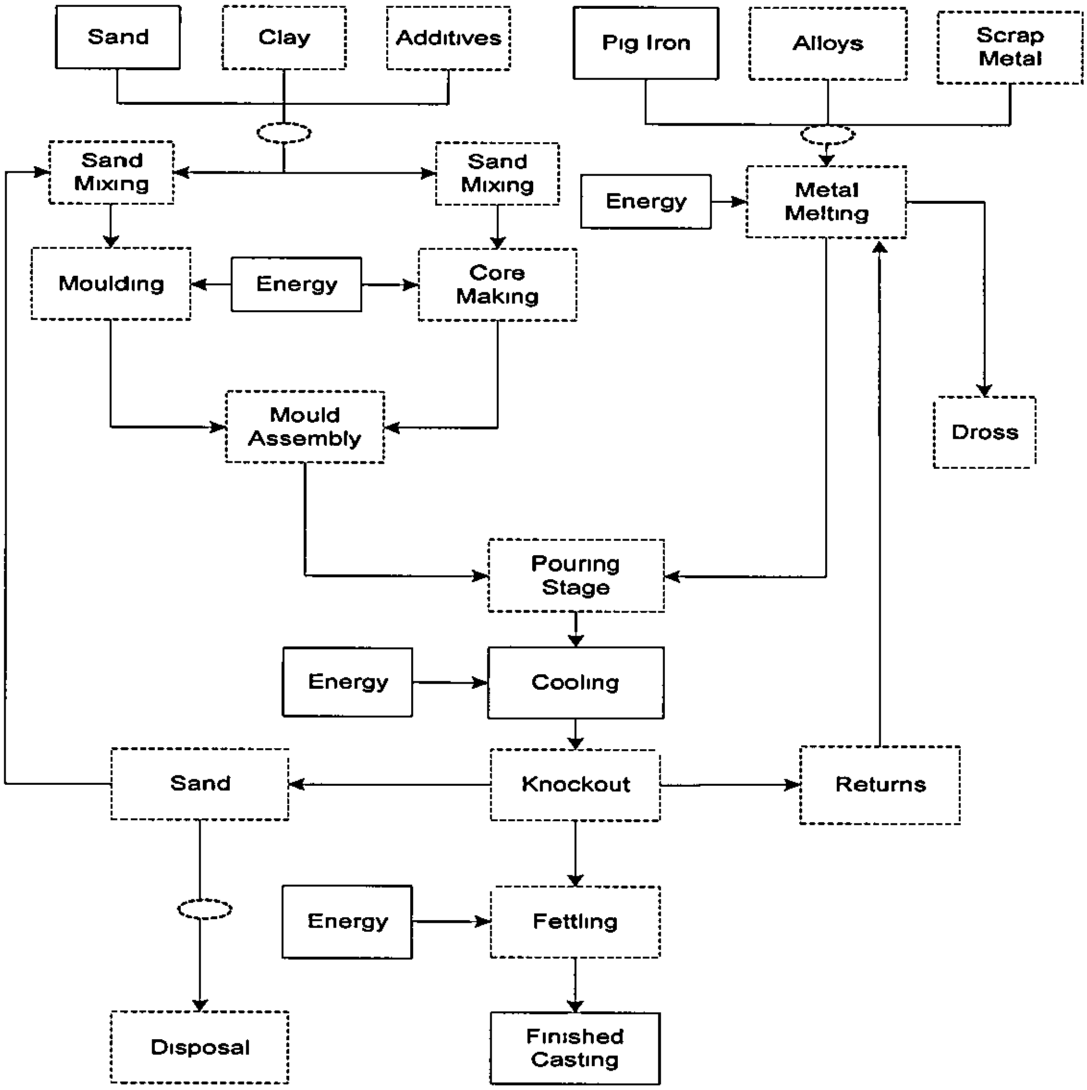


Figure 9: Cast Iron Foundry Process Flow Diagram

4.2.3 Manufacturing and Assembly

This life cycle stage includes processes associated with the transportation of finished castings to the manufacturers, the processes employed by them to make the final component, the assembly of components into a product and finally finishing operations and testing of the final suspension arm.

The study assumes that the processes of the manufacturing and assembly phase are identical for both product systems and, therefore, they are excluded from the calculations of the life cycle inventory. As stated previously, the current LCA study is focused on life cycle stages where preliminary calculations or earlier experience indicate that the difference in environmental impacts can be significant.

The flow diagram of the manufacturing and assembly phase is shown in Figure 10.

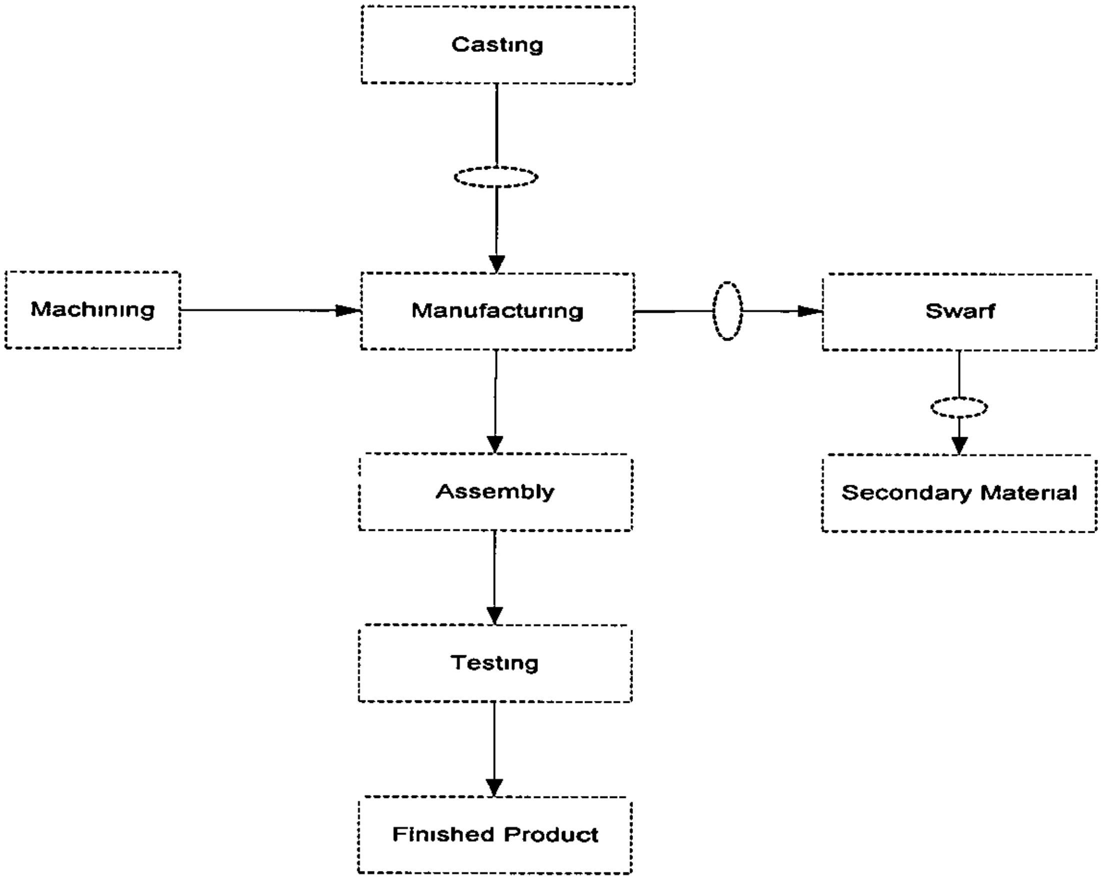


Figure 10: Manufacturing and Assembly Process Flow Diagram

4.2.4 Auto Use Phase

Included in this life cycle stage are the environmental burdens associated with the operation of the vehicle. However, the LCA study covers only the emissions due to fuel production and fuel consumption during the vehicle operation. It is assumed that maintenance requirements would be comparable for both product systems and therefore they are not included in the study. The study also assumed that the fuel used by the automobile is gasoline.

The weight of each part of the vehicle contributes its share to the energy consumed during use. The study assumes that the changes in weight from aluminium to cast iron are linearly proportional to fuel consumption and that the vehicle travels 150,000 km in its lifetime.

The fuel consumption allocated to each suspension arm during the auto use phase is calculated by the following equation (Costic et al., 1998):

$$F = Mp \times L \times \frac{Fe}{Mv} \times \mathrm{C}$$

Where,

F = fuel used over the life cycle of the suspension arm (litres)

Mp = mass of the suspension arm (5 kg and 2.5 kg)

L = lifetime driving distance (150,000 km)

Fe = fuel economy (5.8 litres/100km or 0.058 l/km)

Mv = mass of the vehicle (990kg)

C = Correlation factor of fuel consumption with mass (0.6). This factor means that a weight reduction of 10% leads to a fuel consumption and, consequently, CO_2 emissions reduction of 6%.

The data used in the calculation of the utilization phase are based on the following source (Jenssen, Thiel, 2000).

A flow diagram of the auto use phase is shown in Figure 11.

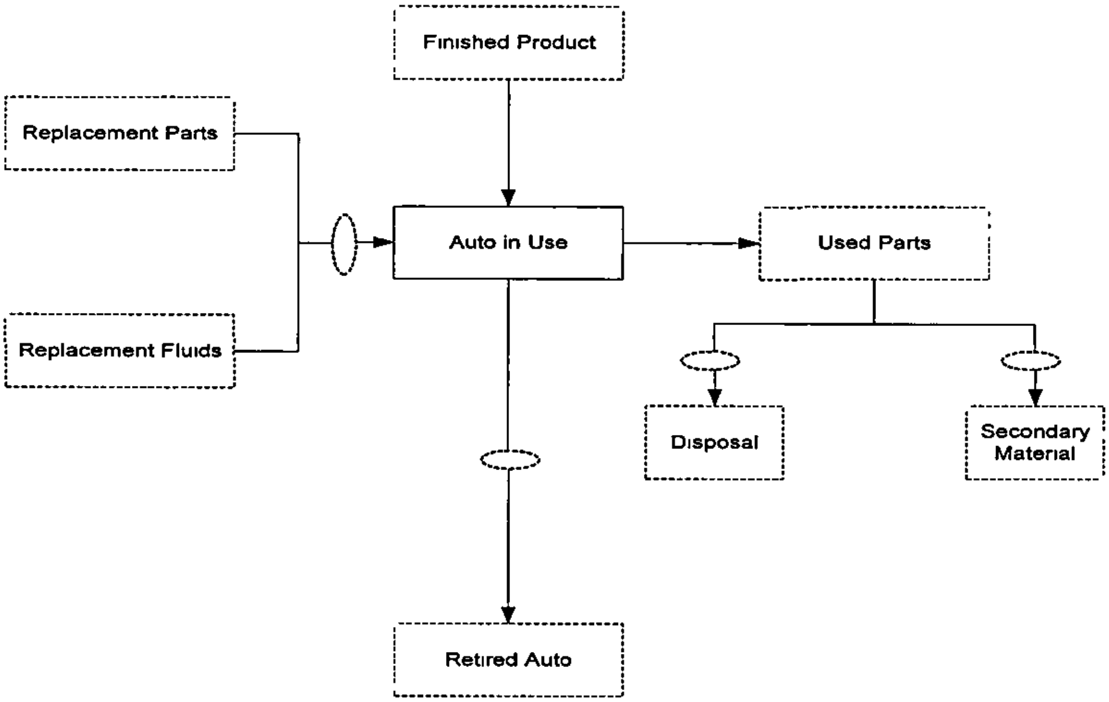


Figure 11: Auto Use Phase Flow Diagram

4.2.5 End-of-Life Management

The last life cycle stage is the vehicle retirement process, which is also known as the end-of-life management process. This life cycle stage includes the dismantling, shredding, materials separation, recycling and disposal of the vehicle materials. Earlier studies have shown that the energy and emissions involved in the end-of-life management process are relatively small (Gibson, 2000).

As already mentioned, the study assumes that the end-of-life management process is almost identical for both aluminium and cast iron product systems and is therefore excluded from the calculations of the life cycle inventory.

A generalized flow diagram indicating the end-of-life management process is provided in Figure 12.

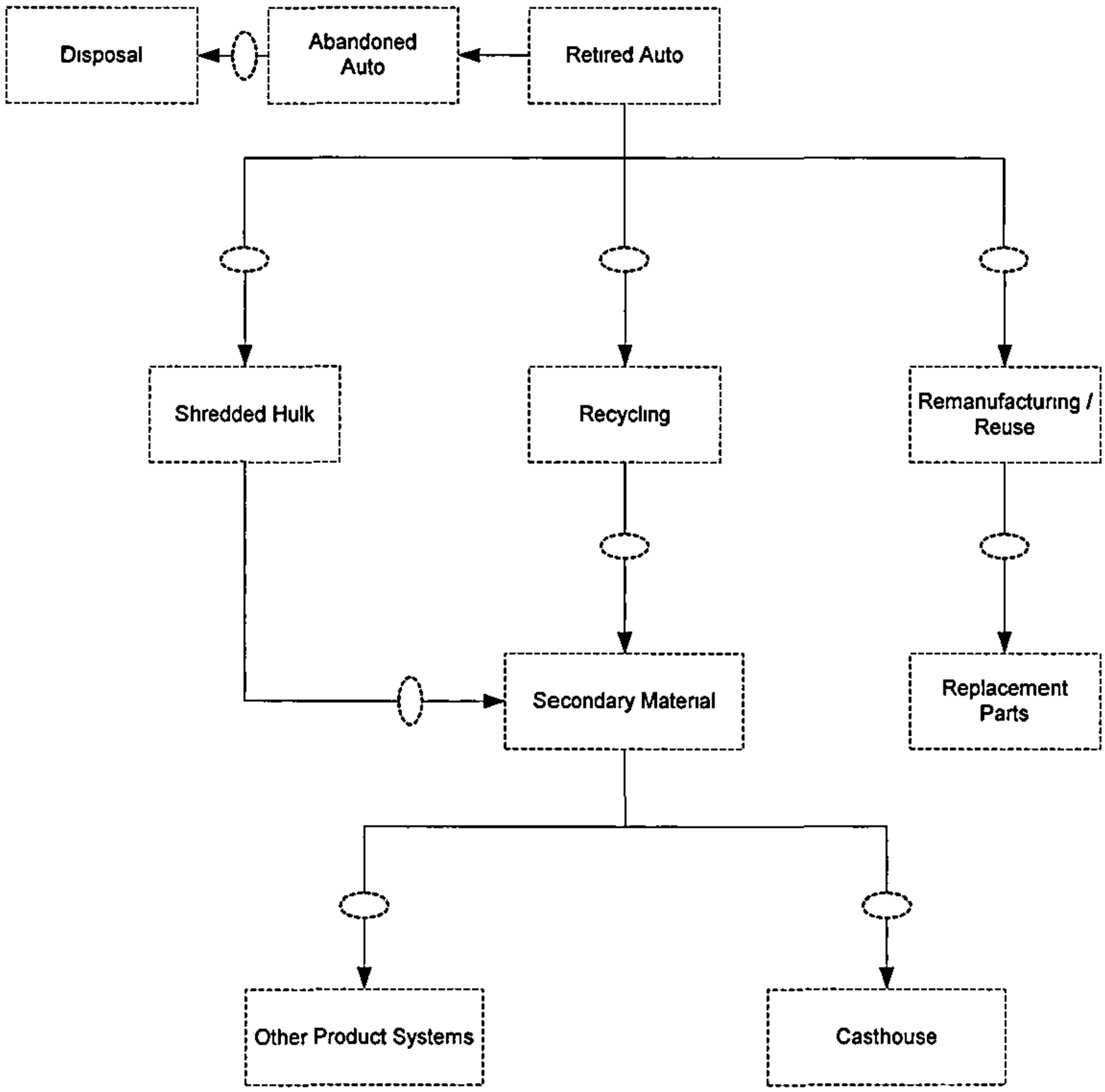


Figure 12: End-of-Life Management Process Flow Diagram

4.3 Summary

The LCA methodology that was used to conduct the comparative study was presented in this chapter. This methodology was based in the requirements of the ISO 14040 standards, which divide the whole LCA process into four phases. Within this chapter, the goal and scope of the study was clearly defined and the functional unit was described: an automotive suspension arm. Detailed flow diagrams were constructed for the different life cycle stages and data collected for every unit operation. Then, all the inputs and outputs were entered into the Boustead LCA Model, which calculates and presents the LCI results for both alternatives product systems.

Chapter 5. Results: Life Cycle Impact Assessment

As seen in Appendices I to X, there is considerable output information derived from the life cycle inventory (LCI) phase. In fact, the output from an LCI represents input and output data and not environmental impacts. The examination of environmental effects, which resulted from environmental releases, is an additional step not covered by the inventory analysis phase. While sometimes LCIs are used as a basis to make product decisions, this is generally difficult to do unless the data categories can be significantly reduced. Life Cycle Impact Assessment (LCIA) is a way to do that.

To demonstrate environmental significance, LCI data should be applied to an LCIA scheme. LCIA aims to examine the product system from an environmental perspective using impact categories and category indicators connected with the LCI results. In fact, this phase supplies additional information that enables the interpretation of the results from the inventory analysis phase.

This chapter presents the results derived form the Life Cycle Impact Assessment (LCIA) phase. The results are presented for both the initial LCA study and the four alternative life cycle scenarios. The different life cycle scenarios were presented in Table 6 in the previous chapter.

The LCIA phase is a three-step process: Selection of impact categories and category indicators, Classification and Characterization.

5.1 Selection of Impact Categories and Category Indicators

To assess the potential impacts of the environmental emissions during the life cycle of the automotive suspension arm, four environmental impact categories have been determined. Every impact category has its own indicator. A category indicator is a metric that represents the environmental mechanism by which the impact category is affecting the environment. The selected environmental impact categories and their category indicators are shown in Table 7.

Impact Category	**Category Indicator**
Global Warming Potential (GWP)	kg CO_2 Equivalents
Acidification Potential	g SO_2 Equivalents
Photo-Oxidant Formation	g C_2H_4 Equivalents
Energy Consumption	MJ Primary Energy Equivalent

Table 7: Selected Impact Categories and Category Indicators

5.2 Classification and Characterization

In fact, classification is the assignment of LCI results to the selected impact categories while characterization is the calculation of category indicator results. This calculation involves the conversion of LCI results to common units and the aggregation of the converted results within the impact category. Classification and characterisation has been performed in one step for both aluminium alloy and cast iron product systems.

5.2.1 Global Warming Potential

Global warming potential (GWP) is associated with the releases of greenhouse gases into the atmosphere. To compare the impacts of emissions of different greenhouse gases, each has been assigned a so-called characterisation factor, expressing the ratio between the emissions of 1 kg of the substance and that due to an equal emission of carbon dioxide (CO_2). In our case, contributions to GWP include not only CO_2 but also CH_4 and CO emissions

Global warming potential with a time perspective of one hundred years (100) is expressed in kg CO_2 equivalents. CO_2 was chosen as a reference compound because it is regarded as being the most significant contributor to the man-made greenhouse effect.

5.2.1.1 Aluminium Alloy Product System

Base Case Scenario

Table 8 shows the GWP of the original aluminium alloy suspension arm and includes the contributions of every substance in the total amount.

Impact Category	Substance	Environment	Quantity (kg)	Characterisation Factor[2]	Result (kg)
Global Warming Potential (100 years)	CH_4	Air	0.189	21	3 969
	CO	Air	0 489	2	0 978
	CO_2	Air	97 066	1	97 066
Total kg CO_2 Equivalents					102 013

Table 8: Aluminium Alloy Global Warming Potential

---

[2] Source: (IPCC, 1996)

Alternative Life Cycle Scenarios

Table 8 presents the GWP of the alternative scenarios for the aluminium alloy suspension arm.

Global Warming Potential	Substance	Quantity (kg)	Characterisation Factor^2	Result (kg)	Total Amount (kg CO_2 Equivalents)
1st Scenario	CH_4	0 159	21	3 339	92 967
	CO	0 485	2	0 970	
	CO_2	88 658	1	88 658	
2nd Scenario	CH_4	0 129	21	2.709	84 079
	CO	0.482	2	0.964	
	CO_2	80 406	1	80 406	
3rd Scenario	CH_4	0 098	21	2 058	74 847
	CO	0 478	2	0 956	
	CO_2	71 833	1	71 833	
4th Scenario	CH_4	0 069	21	1 449	66 142
	CO	0 474	2	0 948	
	CO_2	63 745	1	63 745	

Table 9: Aluminium Alloy Global Warming Potential (Alternative Scenarios)

5.2.1.2 Cast Iron Product System

Base Case Scenario

The GWP of the original cast iron suspension arm, which includes the contributions of every substance in the total amount, is illustrated in Table 10.

Impact Category	Substance	Environment	Quantity (kg)	Characterisation Factor^5	Result (kg)
Global Warming Potential (100 years)	CH_4	Air	0 052	21	1 092
	CO	Air	0 785	2	1.570
	CO_2	Air	84 145	1	84 145
Total kg CO_2 Equivalents					86 807

Table 10: Cast Iron Global Warming Potential

Alternative Life Cycle Scenarios

Table 11 shows the GWP of the alternative life cycle scenarios for the cast iron component and includes the contributions of every substance in the total amount.

Global Warming Potential	Substance	Quantity (kg)	Characterisation Factor[5]	Result (kg)	Total Amount (kg CO_2 Equivalents)
1st Scenario	CH_4	0 051	21	1 071	85 484
	CO	0 757	2	1 514	
	CO_2	82 899	1	82 899	
2nd Scenario	CH_4	0 050	21	1 050	84 159
	CO	0 728	2	1 456	
	CO_2	81 653	1	81 653	
3rd Scenario	CH_4	0 049	21	1 029	82 836
	CO	0 700	2	1 400	
	CO_2	80 407	1	80 407	
4th Scenario	CH_4	0 045	21	0 945	76 237
	CO	0 557	2	1 114	
	CO_2	74 178	1	74 178	

Table 11: Cast Iron Global Warming Potential (Alternative Scenarios)

5.2.2 Acidification Potential

Acidification potential measures the emissions that contribute to acid rain. Acid rain has a wide variety of impacts on soil, groundwater, surface waters, ecosystems and materials (buildings). The major acidifying pollutants are SO_x, NOx, NHx and HCl. Acidification potential is measured in g equivalents of sulphuric acid (SO_2).

5.2.2.1 Aluminium Alloy Product System

Base Case Scenario

The acidification potential of the original aluminium alloy product system, which includes the contributions of every substance in the total amount, is shown in Table 12.

Impact Category	Substance	Environment	Quantity (g)	Characterisation Factor[3]	Result (g)
Acidification Potential	HCl	Air	4 483	0 88	3 945
	NOx	Air	853 324	0 7	597 326
	SO_x	Air	561 897	1	561 897
Total g SO_2 Equivalents					1163 168

Table 12: Aluminium Alloy Acidification Potential

---

[3] Source (Handbook, 2002 p 344)

Alternative Life Cycle Scenarios

Table 13 shows the acidification potential of the alternative life cycle scenarios and includes the contributions of every substance in the total amount.

Acidification Potential	Substance	Quantity (g)	Characterisation Factor[3]	Result (g)	Total Amount (g SO_2 Equivalents)
1st Scenario	HCl	3 734	0 88	3 285	1054 833
	NOx	804 277	0 7	562 993	
	SOx	488 554	1	488 554	
2nd Scenario	HCl	2 998	0 88	2 638	948 501
	NOx	756 138	0 7	529 296	
	SOx	416 567	1	416 567	
3rd Scenario	HCl	2 234	0 88	1 965	838 041
	NOx	706 130	0 7	494 291	
	SOx	341 785	1	341 785	
4th Scenario	HCl	1 513	0 88	1 331	733 836
	NOx	658 953	0 7	461 267	
	SOx	271 238	1	271 238	

Table 13: Aluminium Alloy Acidification Potential (Alternative Scenarios)

5.2.2.2 Cast Iron Product System

Base Case Scenario

Table 14 shows the acidification potential of the original cast iron component, which includes the contributions of every substance in the total amount

Impact Category	Substance	Environment	Quantity (g)	Characterisation Factor[6]	Result (g)
Acidification Potential	HCl	Air	1 070	0 88	0 941
	NOx	Air	877 548	0 7	614 283
	SO_x	Air	313 014	1	313 014
Total g SO_2 Equivalents					928 238

Table 14: Cast Iron Acidification Potential

Alternative Life Cycle Scenarios

The acidification potential of the alternative scenarios for the cast iron suspension arm is shown in Table 15.

Acidification Potential	Substance	Quantity (g)	Characterisation Factor[6]	Result (g)	Total Amount (g SO_2 Equivalents)
1st Scenario	HCl	0 929	0 88	0 817	918 161
	NOx	874.321	0 7	612 024	
	SO_2	305 319	1	305 319	
2nd Scenario	HCl	0 788	0 88	0 693	908 081
	NOx	871 093	0.7	609 765	
	SO_2	297 623	1	297 623	
3rd Scenario	HCl	0 647	0 88	0 569	898 003
	NOx	867 866	0.7	607 506	
	SO_2	289 928	1	289 928	
4th Scenario	HCl	0 058	0 88	0 051	847 710
	NOx	851 728	0 7	596 209	
	SO_2	251 450	1	251 450	

Table 15: Cast Iron Acidification Potential (Alternative Scenarios)

5.2.3 Photo-Oxidant Formation

Photo-oxidant formation is the formation of reactive chemical compounds by the action of sunlight on certain air pollutants. These reactive compounds may be injurious to human health and ecosystems and may also damage crops. Photo-oxidant formation, which is also known as smog, is measured in g of ethylene (C_2H_4) equivalents.

5.2.3.1 Aluminium Alloy Product System

Base Case Scenario

Table 16 shows the potential for photo-oxidant formation of the original aluminium alloy product system and includes the contributions of every substance in the total amount

Impact Category	Substance	Environment	Quantity (g)	Characterisation Factor[4]	Result (g)
Photo-Oxidant Formation	CH_4	Air	189 715	0 007	1 328
	HC	Air	204.767	0 1	20 476
	CO	Air	489 681	0 04	19 587
Total g C_2H_4 Equivalents					41 391

Table 16: Aluminium Alloy Photo-Oxidant Formation

---

[4] Source: (Handbook, 2002 p 342)

Alternative Life Cycle Scenarios

Table 17 shows the potential for photo-oxidant formation of the alternative life cycle scenarios.

Photo-Oxidant Formation	Substance	Quantity (kg)	Characterisation Factor[4]	Result (kg)	Total Amount (g C_2H_4 Equivalents)
1st Scenario	CH_4	159 446	0 007	1 116	40 380
	HC	198 268	0 1	19 826	
	CO	485 945	0 04	19 437	
2nd Scenario	CH_4	129.737	0 007	0 908	39 388
	HC	191.890	0.1	19 189	
	CO	482 278	0 04	19 291	
3rd Scenario	CH_4	98 874	0 007	0 692	38 357
	HC	185 264	0 1	18 526	
	CO	478 468	0 04	19 138	
4th Scenario	CH_4	69 759	0 007	0 488	37 384
	HC	179 012	0 1	17 901	
	CO	474 874	0 04	18 994	

Table 17: Aluminium Alloy Photo-Oxidant Formation (Alternative Scenarios)

5.2.3.2 Cast Iron Product System

Base Case Scenario

The potential for photo-oxidant formation of the original cast iron product system including the contributions of every substance in the total amount, is shown in Table 18.

Impact Category	Substance	Environment	Quantity (g)	Characterisation Factor[7]	Result (g)
Photo-Oxidant Formation	CH_4	Air	52 341	0 007	0 366
	HC	Air	253 002	0 1	25 300
	CO	Air	785 825	0 04	31 433
Total g C_2H_4 Equivalents					57 099

Table 18: Cast Iron Photo-Oxidant Formation

Alternative Life Cycle Scenarios

Table 19 shows the potential for photo-oxidant formation of the alternative life cycle scenarios and includes the contributions of every substance in the total amount.

Photo-Oxidant Formation	Substance	Quantity (kg)	Characterisation Factor[7]	Result (kg)	Total Amount (g C_2H_4 Equivalents)
1st Scenario	CH_4	51 489	0 007	0 360	55 895
	HC	252 452	0 1	25 245	
	CO	757 259	0 04	30 290	
2nd Scenario	CH_4	50 637	0 007	0 354	56 852
	HC	251.902	0 1	25 190	
	CO	782 692	0 04	31 307	
3rd Scenario	CH_4	49 785	0 007	0 348	53 488
	HC	251 352	0.1	25.135	
	CO	700 126	0 04	28 005	
4th Scenario	CH_4	45 524	0 007	0 318	47 470
	HC	248 603	0 1	24 860	
	CO	557 292	0 04	22 291	

Table 19: Cast Iron Photo-Oxidant Formation (Alternative Scenarios)

5.2.4 Energy Consumption

Energy is one of the main parameters considered when conducting an LCA study of automotive components. In fact, energy consumption is a reliable factor, especially for comparison reasons, because much of the emissions, wastes and resources used are caused by the production and consumption of energy or energy carriers.

5.2.4.1 Aluminium Alloy Product System

Base Case Scenario

Table 20 shows the total energy consumption of the original aluminium alloy product system and includes the contributions of every fuel type in the total amount.

Impact Category	Fuel Type	Quantity (MJ)
Energy Consumption	Electricity	704 080
	Oil	929 850
	Other	95 560
Total MJ Primary Energy Equivalents		1729 500

Table 20: Aluminium Alloy Energy Consumption

Alternative Life Cycle Scenarios

Table 21 shows the energy consumption of the alternative life cycle scenarios including the contributions of every fuel type in the total amount.

Energy Consumption	Fuel Type	Quantity (MJ)	Total Amount (MJ Primary Energy Equivalents)
1st Scenario	Electricity Oil Other	567 370 880 870 81 470	1529 72
2nd Scenario	Electricity Oil Other	433 200 832 800 67 640	1333 640
3rd Scenario	Electricity Oil Other	293 810 782 860 53 280	1129 950
4th Scenario	Electricity Oil Other	162.310 735 750 39 720	937 790

Table 21: Aluminium Alloy Energy Consumption (Alternative Scenarios)

5.2.4.2 Cast Iron Product System

Base Case Scenario

Table 22 shows the total energy consumption of the original cast iron product system and includes the contributions of every fuel type in the total amount.

Impact Category	Fuel Type	Quantity (MJ)
Energy Consumption	Electricity Oil Other	61 780 1065 500 82.100
Total MJ Primary Energy Equivalents		1209 380

Table 22: Cast Iron Energy Consumption

Alternative Life Cycle Scenarios

The energy consumption of the alternative life cycle scenarios for the cast iron product system, including the contributions of every fuel type in the total amount, is shown in Table 23.

Energy Consumption	Fuel Type	Quantity (MJ)	Total Amount (MJ Primary Energy Equivalents)
1st Scenario	Electricity Oil Other	59 790 1061 870 66 120	1187 780
2nd Scenario	Electricity Oil Other	57.790 1058 250 50 14	1166.170
3rd Scenario	Electricity Oil Other	55 790 1054 620 34 160	1144 570
4th Scenario	Electricity Oil Other	45 790 1036 490 -45 720	1036 550

Table 23: Cast Iron Energy Consumption (Alternative Scenarios)

5.3 Summary

This chapter covered the outcome of the comparative LCA study. The results were presented for both the base case and the different life cycle scenarios. Four environmental impact categories were determined: global warming potential, acidification potential, photo-oxidant formation and energy consumption.

The results showed that the various environmental impact categories are, however, not equally critical. The contributions to acid rain and photo-oxidant formation are not significant when compared with the consumption of energy potential and the potential for global warming. For this reason, and in accordance with the goal and scope of the study, the focus of the further analysis of the results was placed on global warming potential and energy consumption.

Chapter 6. Analysis: Interpretation Phase

Life Cycle Interpretation is the final phase of the LCA procedure. In this stage the results of both the inventory analysis and the impact assessment phase are summarised and discussed as a basis for conclusions and recommendations in accordance with the goal and scope of the LCA study.

This chapter presents the analysis of the results derived from the previous chapter. The analysis identifies the most significant environmental issues relevant to the two alternative product systems. The two product systems are compared in terms of potential environmental impacts. Finally, initial conclusions are drawn and discussed. These conclusions will form the basis for the final conclusions and recommendations that follow in the next chapter.

The main steps in the interpretation phase are:

- Contribution Analysis
- Comparison of Product Systems
- Discussion of the Results

6.1 Contribution Analysis

The objective of this step is to structure the results from both the LCI and LCIA phases in order to determine the significant issues related with the lifecycle of the two alternative product systems. Contribution analysis answers questions about the contribution of specific environmental flows, processes or impacts to a given environmental score. The LCI and LCIA results will be structured in accordance with the different processes in order to identify the contribution of each of the five life cycle stages to the total calculated amount. The contributions are usually expressed as percentages. In the contribution analysis, the most important processes are identified for each environmental impact as well as the most important emissions for these processes.

The focus of the contribution analysis will be placed on air emissions and, more specifically, global warming potential as well as energy consumption associated with the different life stages of both the aluminium alloy and the cast iron product systems.

6.1.1 Global Warming Potential

6.1.1.1 Aluminium Alloy Product System

Base Case Scenario

The potential contribution to global warming of the different product life stages of the original aluminium suspension arm is summarised in Figure 13.

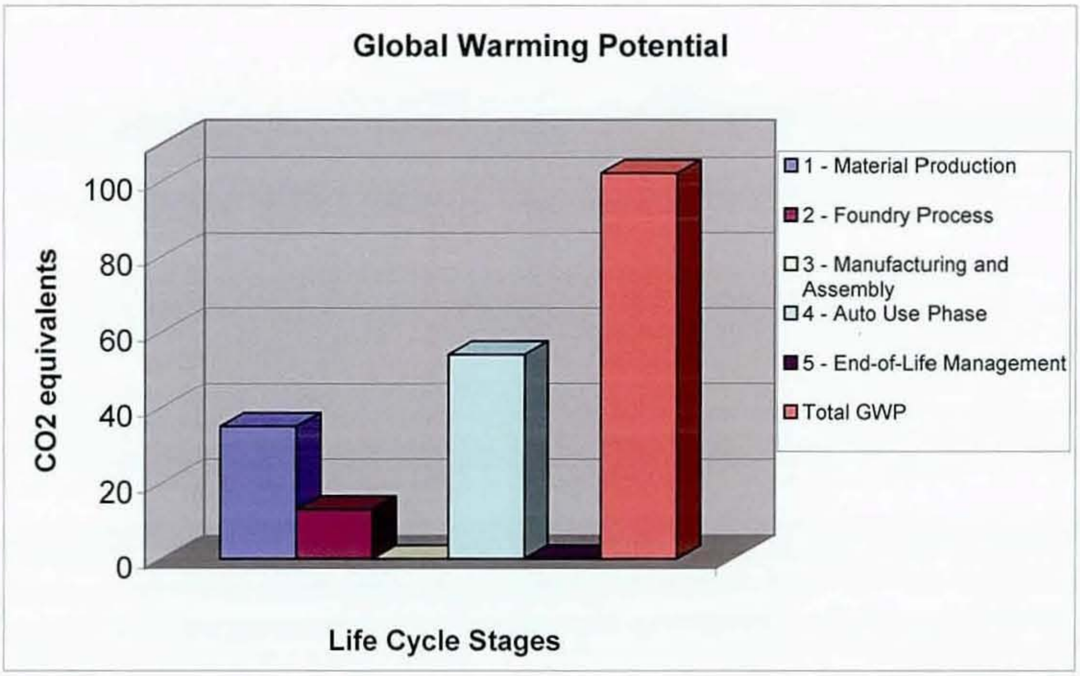


Figure 13: Aluminium Alloy GWP from a Life Cycle Stages Perspective

The total life cycle inventory of greenhouse gases (102.029 kg of CO_2 equivalents) for the original aluminium suspension arm is dominated by the intensive consumption of gasoline in the use phase of the automobile (53.969 kg of CO_2 equivalents). Consequently, the auto use phase accounts for 52% of the global warming potential (GWP). Additionally, the material production phase contributes 34% and the foundry process the remaining 14% of the total global warming potential over the life cycle of the product system.

Regarding the main contributor to global warming, Table 8, in the previous chapter, has shown that CO_2 is the dominating substance in this impact category contributing about 95% of the total global warming potential.

Alternative Life Cycle Scenarios

Figure 14 shows the potential contribution to global warming of the alternative aluminium alloy scenarios including the contributions of every life cycle stage in the total amount.

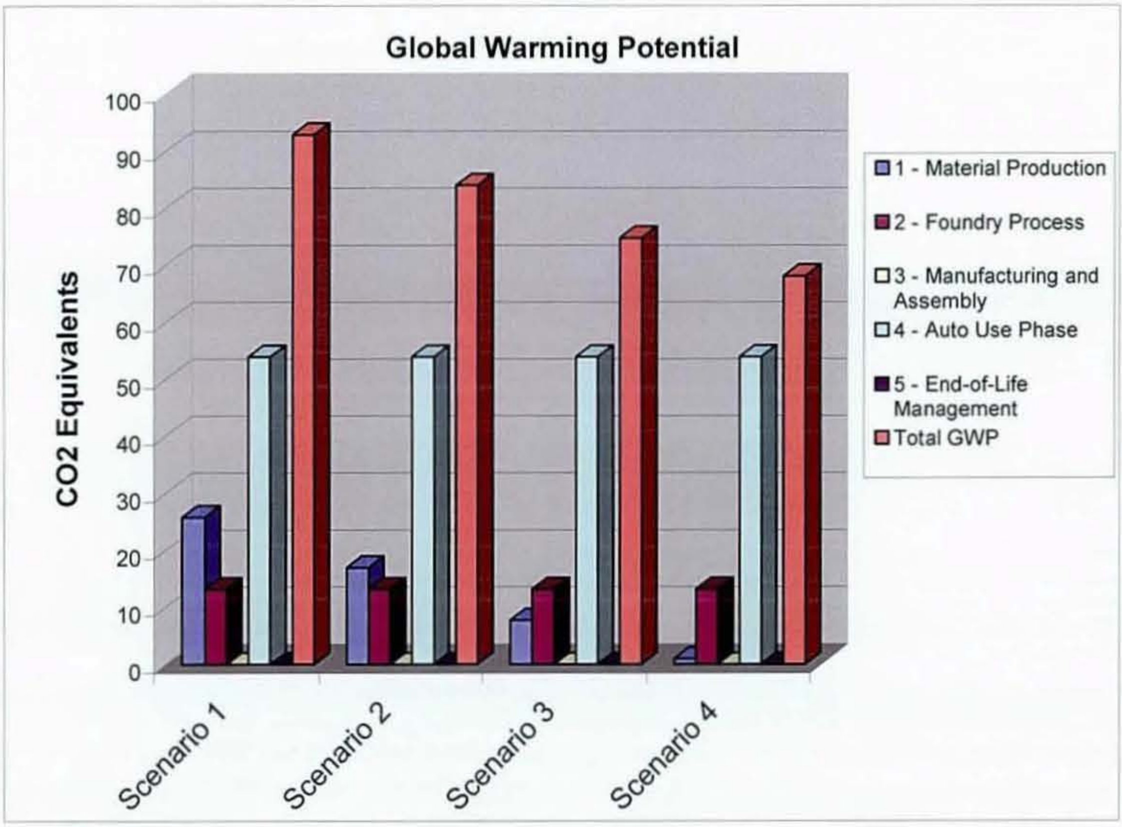


Figure 14: Aluminium Alloy GWP from a Life Cycle Stages Perspective (Alternative Scenarios)

A comparison of the four life cycle scenarios clearly shows that the global warming potential of the aluminium product system is significantly reduced as the percentage of the secondary aluminium is increased. The 4^{th} scenario (100% Secondary Material) gives almost 25 kg less CO_2 equivalents compared with the 1^{st} scenario (75% Virgin-25% Secondary Material) a decrease of about 27% between the two alternatives.

It should be noted that two of the life cycle stages, the foundry process and the auto use phase, are not affected by the proportional changes of the secondary aluminium share. These variations only affect the material production phase of the aluminium product system.

6.1.1.2 Cast Iron Product System

Base Case Scenario

The contribution to global warming potential of the different product life stages of the original cast iron component is shown in Figure 15.

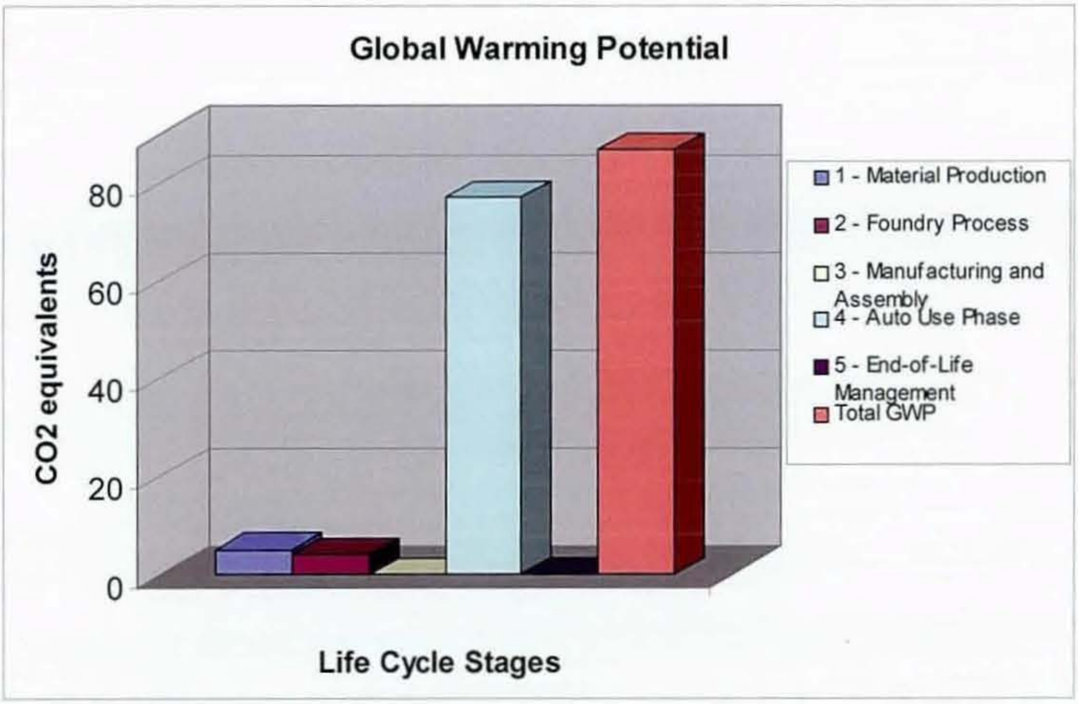


Figure 15: Cast Iron GWP from a Life Cycle Stages Perspective

The auto use phase (77.116 kg of CO_2 equivalents) obviously dominates the total global warming potential of the cast iron product system (86.815 kg of CO_2 equivalents). This particular life cycle stage accounts for approximately 89% of the total amount of global warming potential. The material production phase and the foundry process share the remaining 11%.

Once again, CO_2 is the dominating substance in this impact category contributing about 97% of the total amount of greenhouse gases.

Alternative Life Cycle Scenarios

The potential contribution to global warming of the alternative scenarios for the cast iron component, including the contributions of every life cycle stage in the total amount, is illustrated in Figure 16.

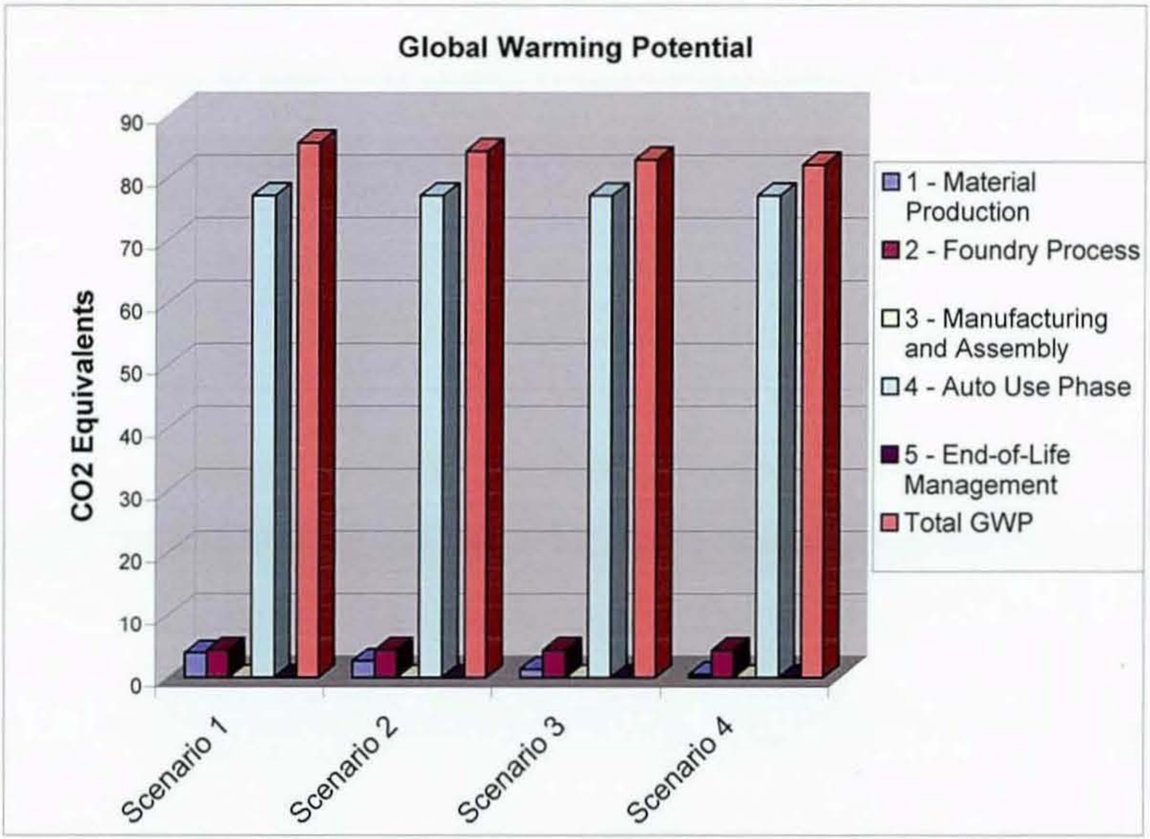


Figure 16: Cast Iron GWP form a Life Cycle Stages Perspective (Alternative Scenarios)

Figure 16 shows that the total global warming potential of the cast iron product system is not particularly affected by the change of the secondary material percentage. In fact, GWP is only reduced by 3.5% between the 1st and the 4th scenario. This is due to the limited contribution of the material production phase in the total GWP of the cast iron product system.

6.1.2 Energy Consumption

6.1.2.1 Aluminium Alloy Product System

Base Case Scenario

The energy consumption of the original aluminium product system, including the contributions of every life cycle stage in the total amount, is shown in Figure 17. Each of the energy bars is further subdivided to show the relative contributions of different energy resources.

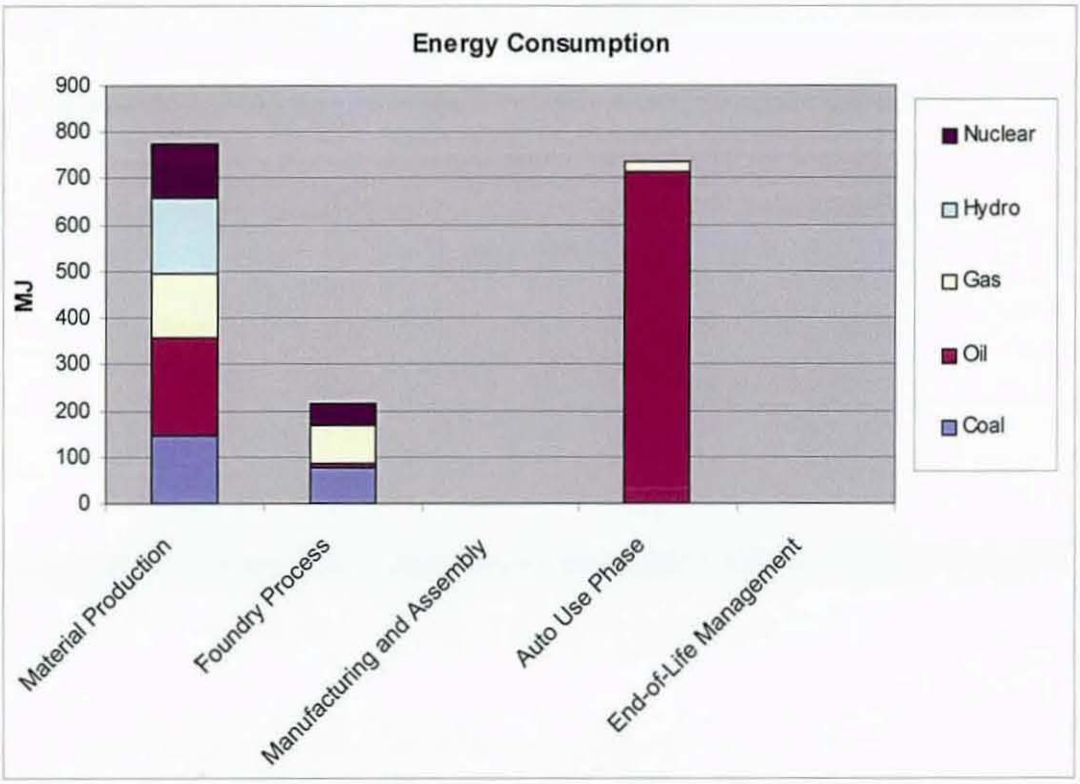


Figure 17: Energy Consumption for the Aluminium Alloy Product System

Most of the energy of the aluminium alloy product system is consumed during material production (45%) followed by the auto use phase (42.5%). The foundry process contributes about 12.5% of the total amount.

Figure 17 also shows that the share of the different energy resources is partly divided between the material production phase and the foundry process. On the other hand, the auto use phase is clearly dominated by the share of oil and, more specifically, gasoline.

Alternative Life Cycle Scenarios

The energy consumption of the alternative aluminium alloy product systems is shown in Figure 18.

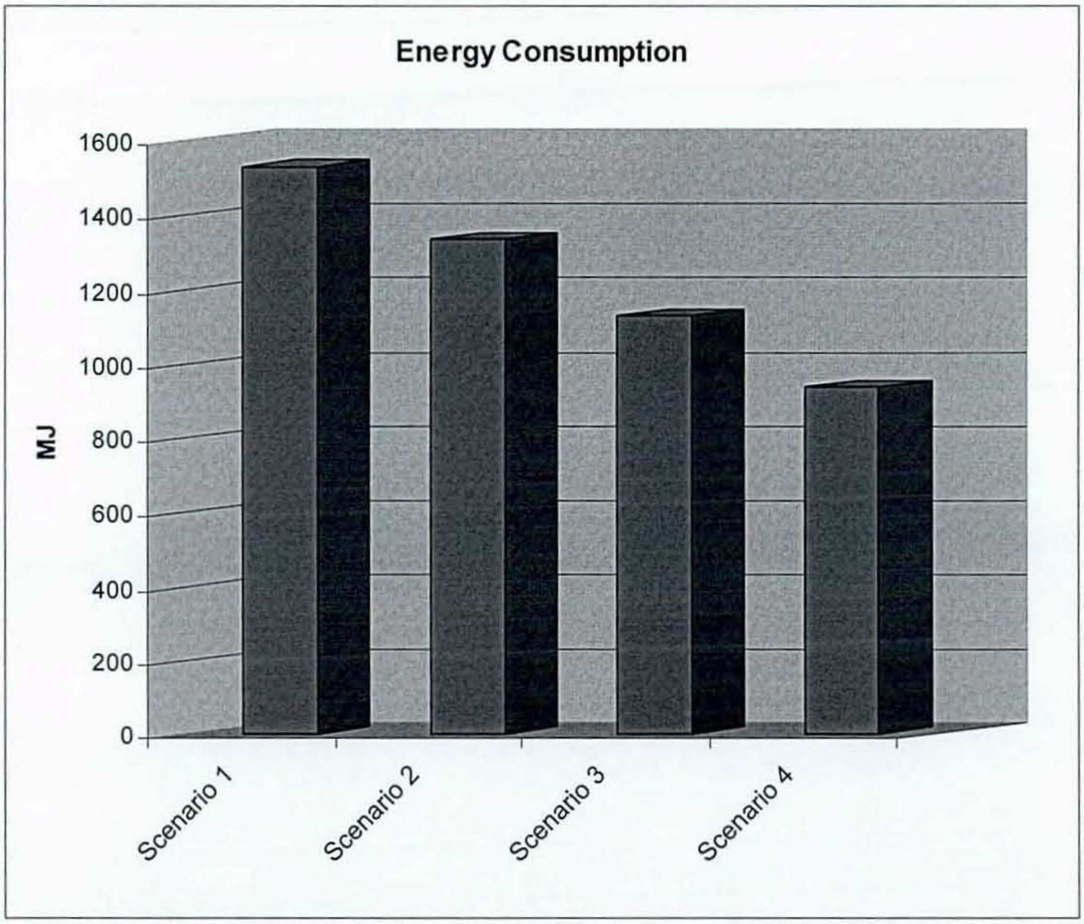


Figure 18: Energy Consumption for the Aluminium Alloy Product Systems (Alternative Scenarios)

A comparison of the four life cycle scenarios shows that the energy consumption is progressively reduced as the percentage of the secondary aluminium increased within the different scenarios. For instance, the 4th scenario requires almost 600 MJ less energy compared with the 1st scenario. This corresponds to a decrease of about 39% in the energy consumption.

6.1.2.2 Cast Iron Product System

Base Case Scenario

The energy consumption of the original cast iron product system, including the contributions of every life cycle stage in the total amount, is shown in Figure 19. Furthermore, each of the energy bars is subdivided to show the relative contributions of different energy resources.

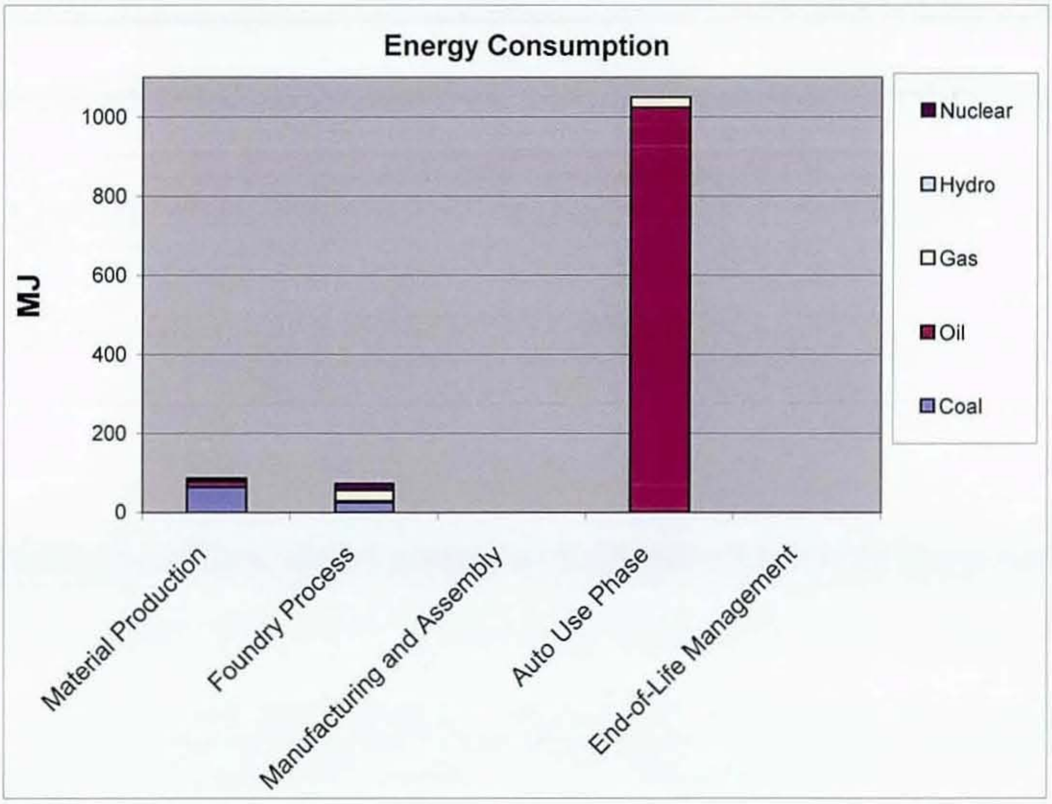


Figure 19: Energy Consumption for the Cast Iron Product System

The above figure shows that the energy consumption of the cast iron product system is certainly dominated by the use phase of the automobile. Almost 87% of the total energy is consumed during this particular life cycle stage. The material production phase and the foundry process share the remaining 13% of the total amount.

As regards the share of the different energy resources, the share of oil dominates the use phase and, generally, the total energy consumption.

Alternative Life Cycle Scenarios

Figure 20 shows that the total energy consumption of the cast iron product system is not particularly affected by the percentage change of the secondary material. The consumption of energy is only reduced by 2% between the 1st and the 2nd scenario and approximately 12.7% between the 1st and the 4th scenario.

The energy consumption of the alternative cast iron product systems is shown in Figure 20.

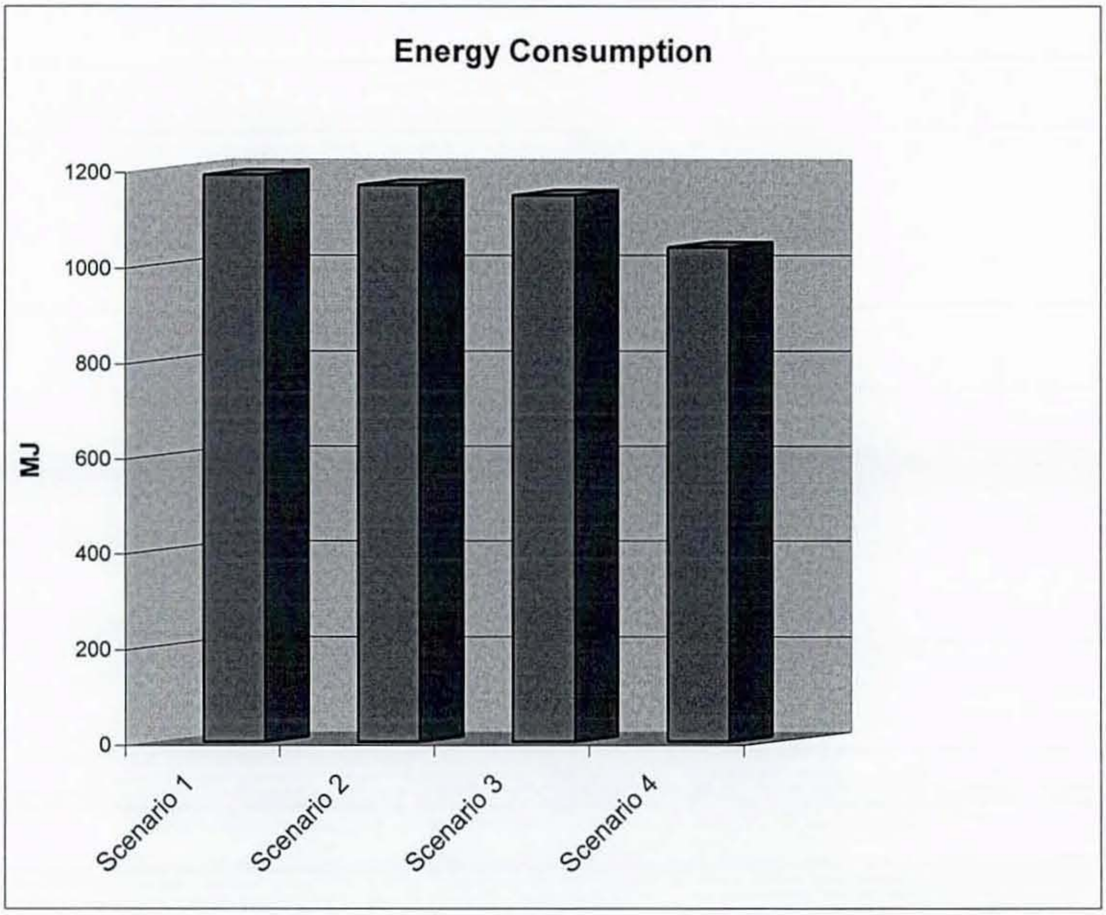


Figure 20: Energy Consumption for the Cast Iron Product Systems (Alternative Scenarios)

6.2 Comparison of Product Systems

The LCI and LCIA results for the material production, foundry process, manufacturing and assembly, auto use and end-of-life management stages of the automotive suspension components have been determined. The contribution analysis shows a wide range of environmental and energy differences between the two material groups.

This sub-chapter attempts to compare the two product systems in terms of potential environmental impacts. In particular, the comparison will be focused on global warming potential and energy consumption, which comprise the two most important aspects of the results. Finally, the break-even point between the two product systems will be established.

6.2.1 Comparability of the Product Systems

According to ISO, *"product systems shall be compared using the same functional unit and equivalent methodological considerations"* (ISO 14040, 1997, p.6). The term "*methodological considerations*" might include system boundaries, data quality, environmental impacts and impact assessment method.

As already mentioned, the same functional unit is used in the studies of each individual product system: an automotive suspension arm. The technical specifications of the two suspension arms are identical which ensures that the functional unit is well defined and that the two alternatives are comparable. The only difference is the weight of the functional unit due to lower density of the aluminium component.

The same criteria have also been used for defining the system boundaries of the two product systems. Both LCA studies are designed as "*cradle to grave*" studies including all the environmental burdens associated with the product systems over the entire life cycle of the two suspension arms.

Finally, it should be noted that no particular impact assessment method has been applied to this comparative LCA study. Impact assessment methods such as Eco-indicator 99 and EDIP, make use of three additional LCIA steps: normalisation, grouping and weighting. However, these three steps are considered optional under the ISO 14040 standards and for this reason are excluded from the current study.

6.2.2 Global Warming Potential

Base Case Scenario

The total global warming potential of the aluminium alloy product system (102.029 kg of CO_2 equivalents) is almost 15% higher than the global warming potential of the cast iron system (86.815 kg of CO_2 equivalents).

The major differences between the two material groups are apparently concentrated in the material production and the auto use phases. The GWP of the material production for the aluminium alloy component is about 7 times higher than it is for the production of the cast iron. On the other hand, the GWP of the auto use phase for the cast iron is about 30% more compared with the aluminium alloy component due to the effect on fuel consumption of the heavier cast iron component.

Figure 21 shows the global warming potential resulting from the two analysed material alternatives throughout their life cycle including the contributions of every life cycle stage in the total amount.

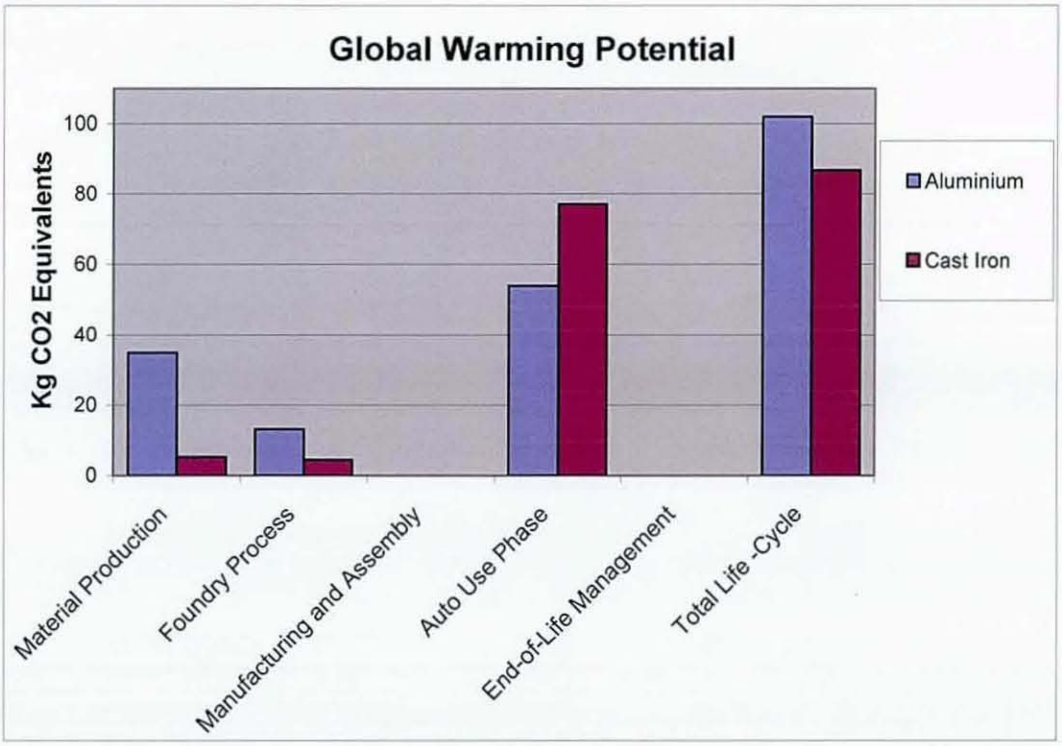


Figure 21: Comparative Global Warming Potential

Alternative Life Cycle Scenarios

A comparison of the four life cycle scenarios demonstrates that the cast iron product system gives better GWP results only in the 1st scenario while the aluminium alloy product system performs better within the 3rd and 4th scenarios. A balance between the two alternatives is achieved within the 2nd scenario when both materials are produced using 50% virgin and secondary material.

As the GWP of the aluminium alloy product system is reduced by a rate of almost 10% within the different life cycle scenarios respectively, the GWP of the cast iron product system is reduced by only 3%. This is due to the major differences between the two alternative product systems in the material production and auto use phases.

Figure 22 shows the potential contribution to global warming of the alternative life cycle scenarios for both product systems.

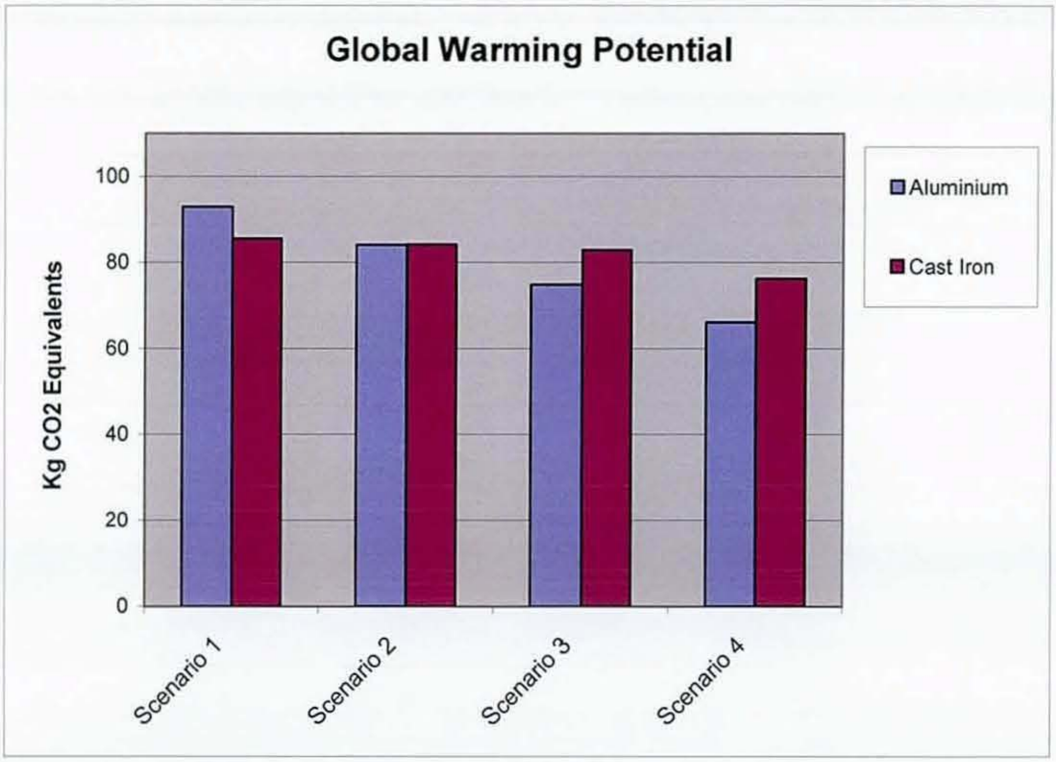


Figure 22: Comparative Global Warming Potential (Alternative Scenarios)

6.2.3 Energy Consumption

Base Case Scenario

The total energy consumption of the aluminium alloy product system is almost 30% higher compared with the energy that is consumed in the cast iron product system. Once more, the analysis has shown that there is a wide gap between the two material groups in the material production and the auto use phases.

The energy required for the production of the aluminium alloy suspension arm is about 9 times higher than it is for the production of the cast iron alternative. Most of the aluminium production energy is consumed during the electrolysis process and from the alumina production process. Conversely, the auto use phase of the cast iron component requires almost 30% more energy compared with the aluminium alloy component. Additionally, the foundry process of the aluminium product system needs almost 3 times more energy compared with the cast iron.

The energy consumption of the two alternative product systems, including the contributions of every life cycle stage in the total amount, is shown in Figure 23.

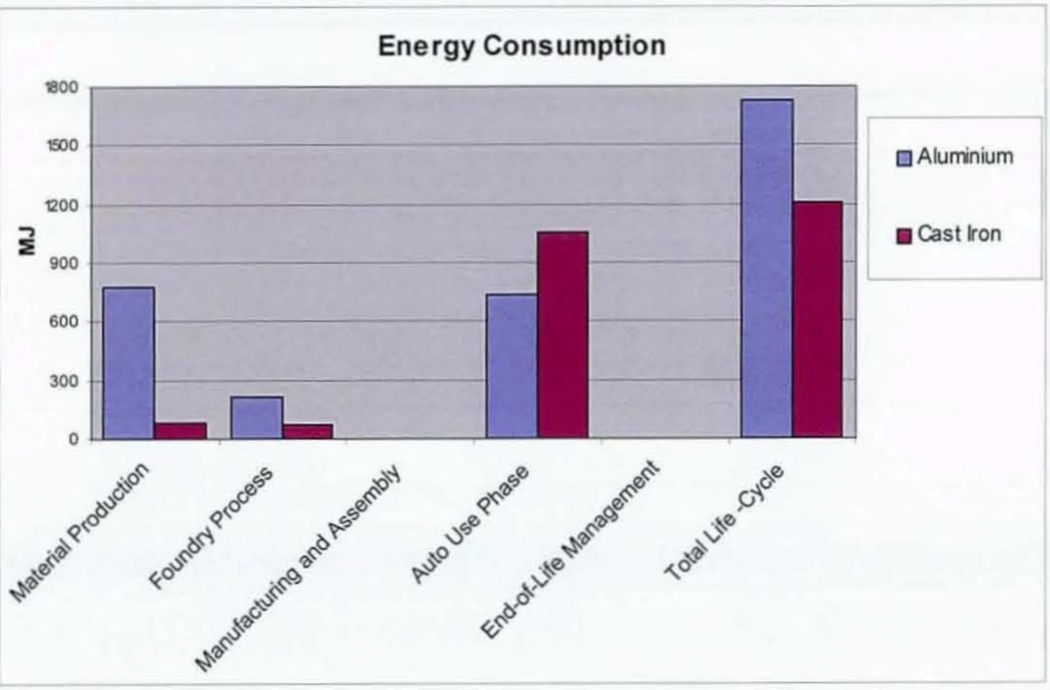


Figure 23: Comparative Energy Consumption

Alternative Life Cycle Scenarios

Figure 24 shows the energy consumption of the alternative life cycle scenarios for both aluminium alloy and cast iron product systems.

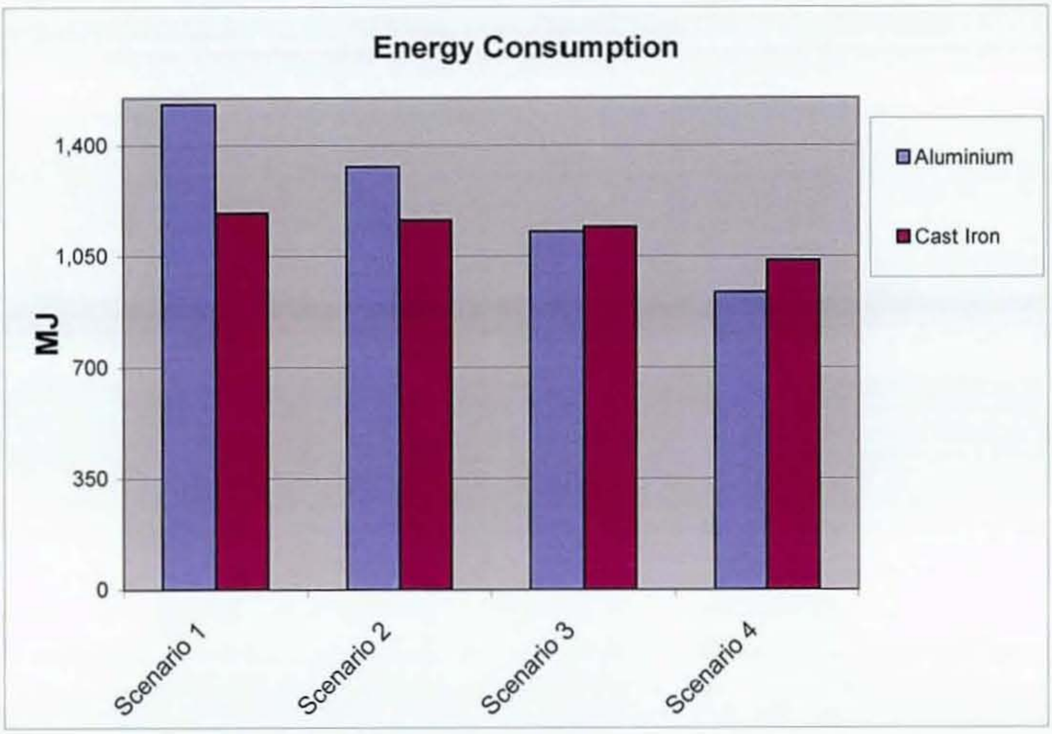


Figure 24: Comparative Energy Consumption (Alternative Scenarios)

The energy comparison of the different life cycle scenarios shows that the aluminium alloy product system consumes more energy in the 1st scenario and 2nd scenario but requires less energy in the 3rd and 4th scenarios. A balance between the two alternatives is almost achieved within the 3rd scenario when the cast iron product system consumes only 15 MJ more energy than the aluminum alloy alternative. Finally, in the 4th scenario (100% Secondary Material), the aluminium alloy product system requires almost 9.5% less energy than the alternative cast iron product system.

6.2.4 Break-Even Point

Base Case Scenario

Figure 25 shows the global warming potential of the two material groups in relation to vehicle use. Global warming potential, measured in kg of CO_2 equivalents, is displayed along the y-axis while kilometres travelled, the dependant variable, is shown along the x-axis. The values shown at 0 kilometres represent the GWP of the material production phase and foundry process.

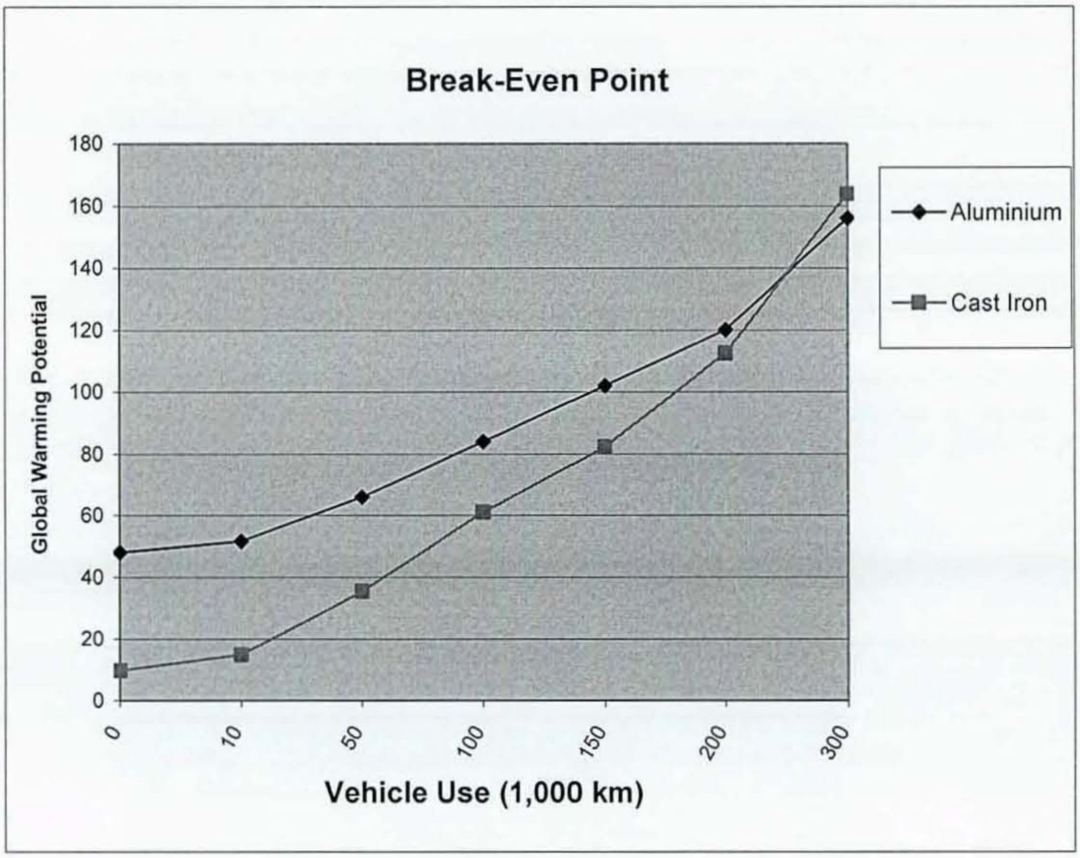


Figure 25: Break-Even Point Between Aluminium and Cast Iron

The figure shows that the cast iron component has a clear advantage at the beginning of the curve because of the high-energy demand during the aluminium production phase. However, the gap between cast iron and aluminium is gradually reduced. However it takes many kilometres for the aluminium suspension arm to reach the break-even point with the cast iron components. The break-even point for the aluminium suspension arm in comparison to the cast iron component along the entire life cycle is at about 250,000 km.

1st Life Cycle Scenario

Figure 26 identifies the break-even point between the two material groups in the case of the 1st scenario (75% Virgin-25% Secondary Material).

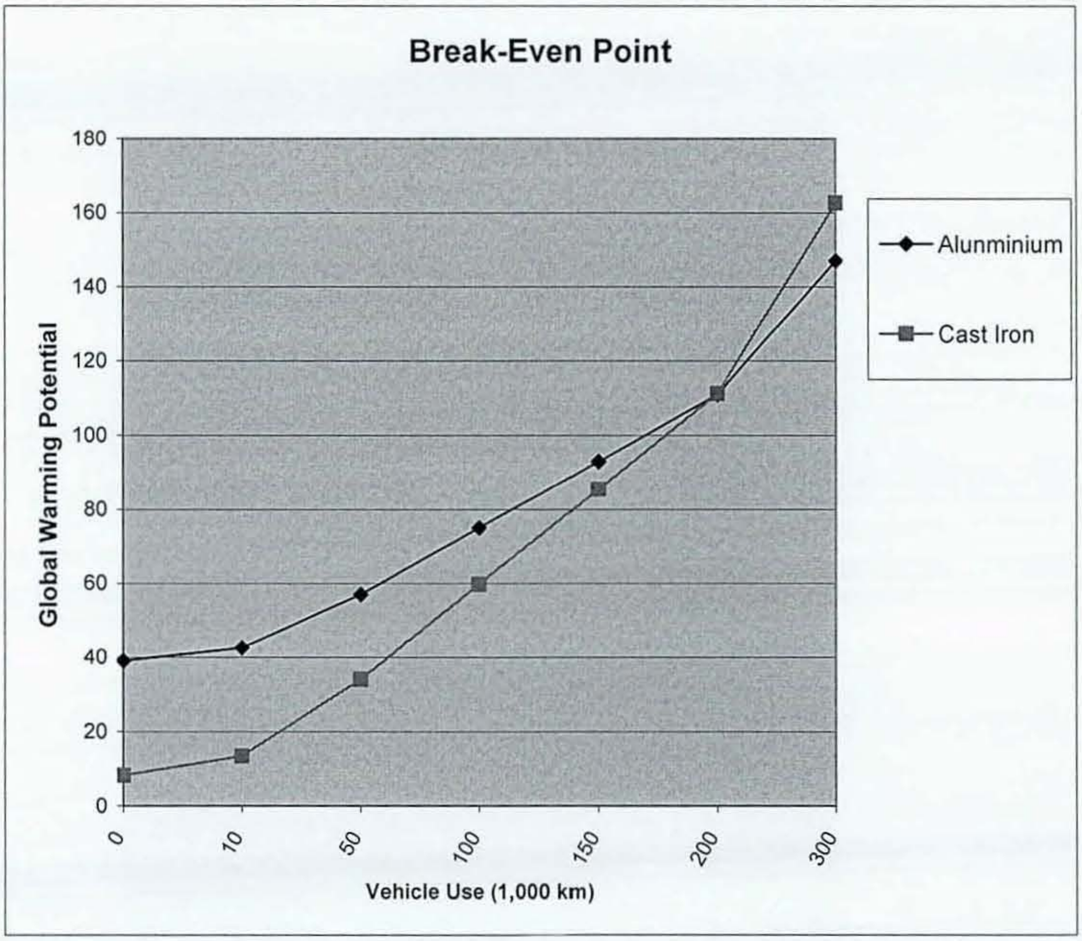


Figure 26: Break-Even Point Between Aluminium and Cast Iron (1st Scenario)

Figure 26 shows a similar picture with the base case scenario. The cast iron component has a clear advantage at the beginning of the curve which is gradually reduced. In this case, the break-even point for the aluminium suspension arm in comparison to the cast iron component along the entire life cycle is at about 200,000 km.

2^{nd} Life Cycle Scenario

The break-even point between the two material groups, in the case of the 2^{nd} scenario (50% Virgin-50% Secondary Material), is shown in Figure 27.

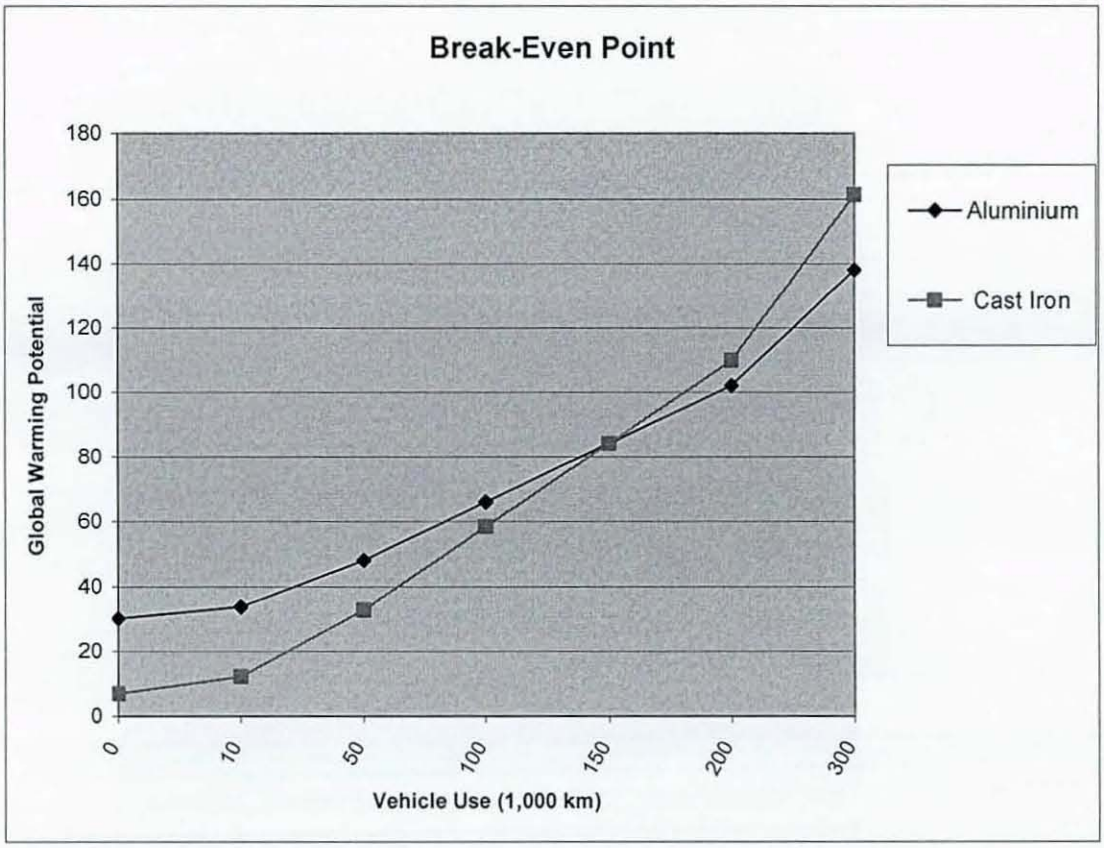


Figure 27: Break-Even Point Between Aluminium and Cast Iron (2^{nd} Scenario)

In this particular scenario, the break-even point between the aluminium product system and the cast iron component is established at around 150,000 km.

3^{rd} Life Cycle Scenario

The break-even point between the two alternative material groups, in the 3^{rd} life cycle scenario (25% Virgin-75% Secondary Material), is shown in Figure 28.

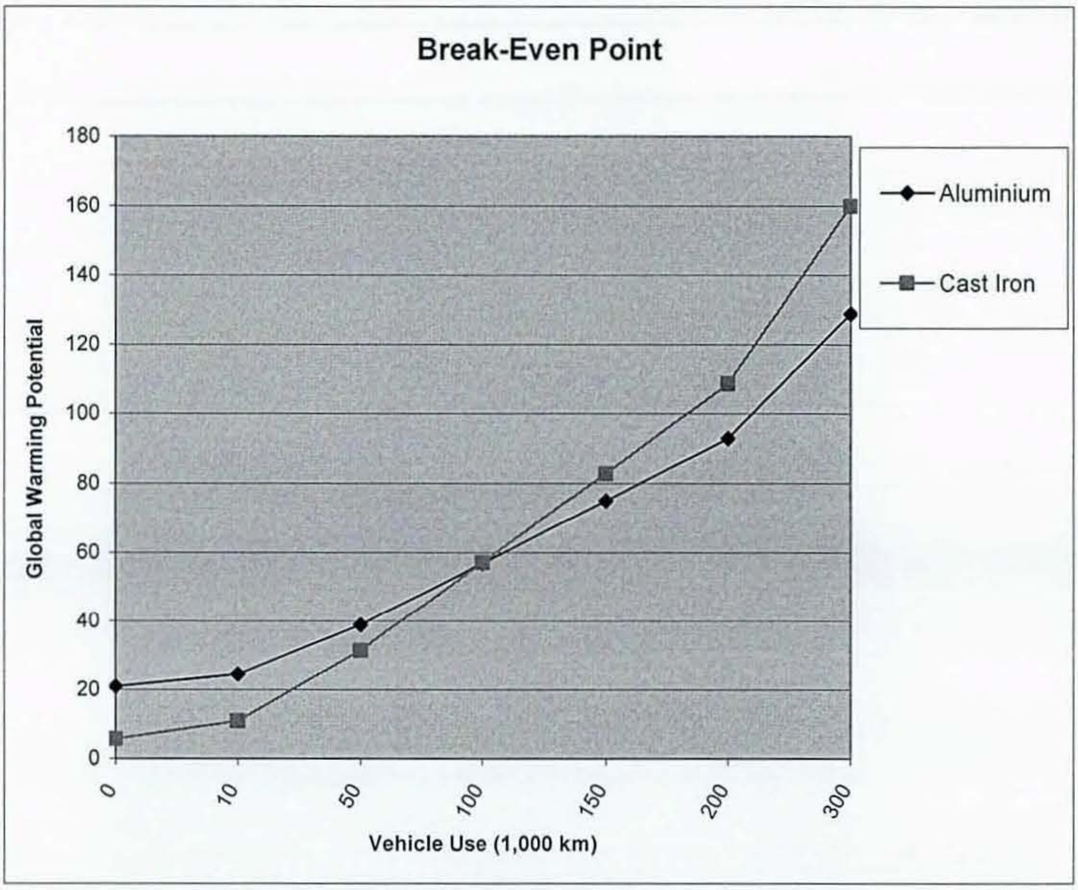


Figure 28: Break-Even Point Between Aluminium and Cast Iron (3rd Scenario)

In the 3rd life cycle scenario, the break-even point between the aluminium product system and the cast iron component occurs much earlier compared with the previous scenarios. In this case, the break-even point was established at around 100,000 km.

4th Life Cycle Scenario

Figure 26 identifies the break-even point between the two material groups in the case of the 4th life cycle scenario (100% Secondary Material).

The figure shows that the advantage of the cast iron product system, with the smallest global warming potential during the material production phase, is countered by much higher fuel consumption during the use phase due to the weight of the cast iron suspension arm.

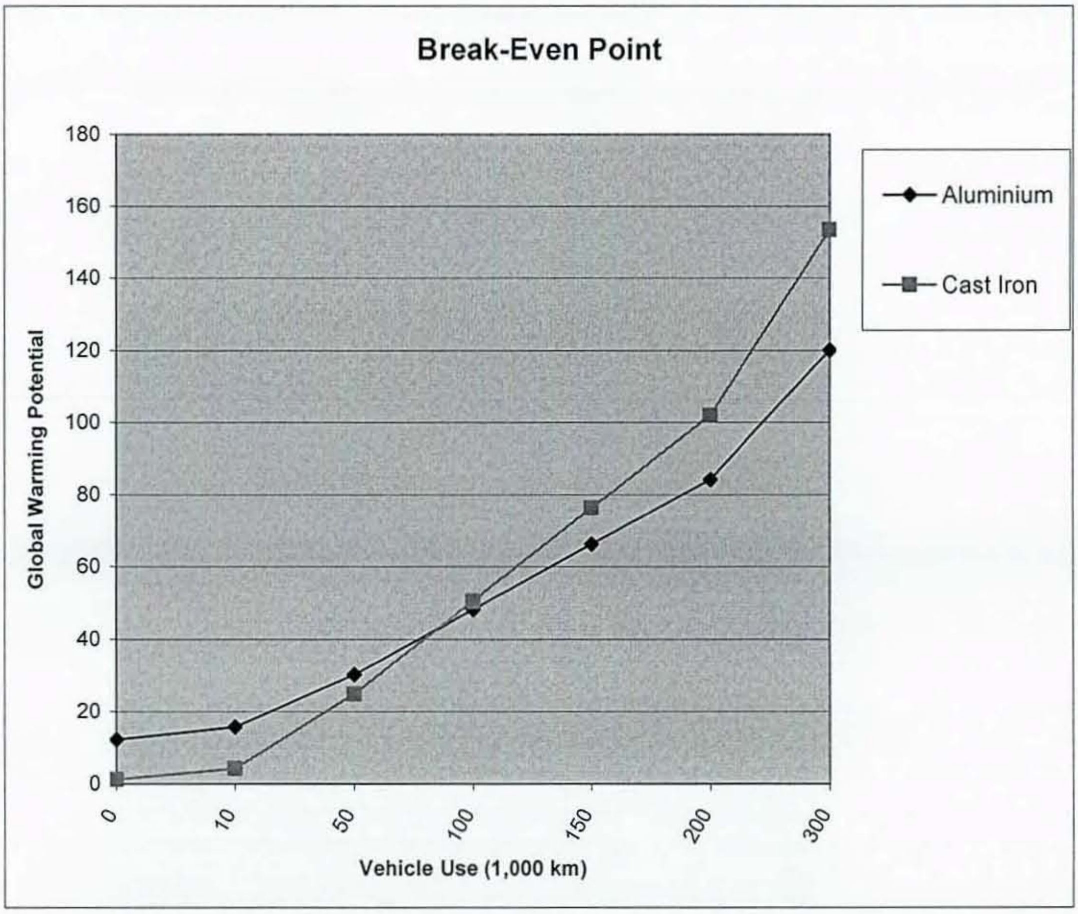


Figure 29: Break-Even Point Between Aluminium and Cast Iron (4th Scenario)

In this life cycle scenario, the break-even point between the two alternative components occurs at about 75,000 km.

6.3 Discussion of the Results

Although the results show that the auto use phase is the dominating contribution to most of the environmental impacts, the contribution of the other life cycle stages is also considerable. When comparing the material choice of aluminium alloy vs. cast iron for a suspension arm in terms of the presented environmental criteria, many trade-offs become apparent. For example, energy saved in the use phase can be overwhelmed by the material production phase for the aluminium alloy case. This is highly dependant on the amount of secondary material available for the automotive component.

Hence, it is important to have a picture of where in the suspension arm product system the potential global warming and energy consumption arise. This will help to evaluate further the environmental contribution of each life cycle stage.

Table 24 shows the percentage of potential contribution to global warming of the different life cycle stages for the two alternative product systems.

Alternative Product Systems		Base Case Scenario (%)	1st Scenario (%)	2nd Scenario (%)	3rd Scenario (%)	4th Scenario (%)
Aluminium Alloy	*Material Production*	52	28	20	10	2
	Foundry Process	14	14	16	18	19
	Auto Use Phase	34	58	64	72	79
Cast Iron	*Material Production*	6	5	3	2	1
	Foundry Process	5	5	5	5	5
	Auto Use Phase	89	90	92	93	94

Table 24: Potential Contribution of the Different Life Cycle Stages to Global Warming

Table 25 shows the energy consumption contribution of the different life cycle stages for the two alternative product systems.

Alternative Product Systems		Base Case Scenario (%)	1st Scenario (%)	2nd Scenario (%)	3rd Scenario (%)	4th Scenario (%)
Aluminium Alloy	*Material Production*	45	38	29	16	2
	Foundry Process	13	14	16	19	23
	Auto Use Phase	42	48	55	65	78
Cast Iron	*Material Production*	8	6	4	2	2
	Foundry Process	6	6	6	6	5
	Auto Use Phase	86	88	90	92	93

Table 25: Energy Consumption Contribution of the Different Life Cycle Stages

6.3.1 Material Production Phase

The material production phase contributes most significantly in the case of the aluminium alloy product system. This is due to the higher energy demand during the production of primary aluminium. Additionally, large amounts of carbon dioxide (CO_2) emissions arise through combustion of fuels in bauxite mining, alumina refining, anode production and cast house production processes. On the other hand, secondary aluminium requires less energy and, consequently, emits less greenhouse gases than the primary aluminium production. In general, the more secondary aluminium is used the less significant is the contribution of the material production phase in the total environmental burden.

The energy consumed in the production of cast iron is considerably lower compared to aluminium. This leads to lower greenhouse gases emissions during the production of cast iron and, consequently, significantly lower global warming potential for all the life cycle scenarios of the cast iron product system.

6.3.2 Foundry Process

The foundry process is mainly divided into the melting process, where metal is melted at high temperatures, and the moulding process where a mould is prepared into which molten metal is poured. It is obvious that of these two processes the melting process consumes most of the energy and releases most of the greenhouse gases into the atmosphere.

In the case of the aluminium alloy, the contribution of the foundry process to the total energy consumption and global warming potential is relatively stable and ranges between 13 and 23% of the total amount. The more secondary aluminium is used the more significant is the contribution of the foundry process to the total environmental burden. Conversely, the cast iron foundry process contributes less to the total environmental burden than the aluminium alloy alternative in each life cycle scenario.

6.3.3 Auto Use Phase

The use phase is the most significant life cycle stage in the suspension arm product system, which contributes to environmental impact potentials on a large scale. The main factor is the gasoline consumption during the operation phase of the automobile.

The use phase of the cast iron suspension arm, which is the heaviest component, gives the higher contribution to the total impact on the environment. This contribution is relatively stable and ranges between 86 and 94 % for the different life cycle scenarios. On the other hand, in the aluminium alloy case, the more secondary material is used the more significant is the contribution of the auto use phase to the total environmental burden.

6.4 Strengths and Weaknesses of the LCA Methodology

The LCA methodology offers many advantages and benefits when used as a tool for identifying the environmental impacts of metal castings at various stages of their life cycle. LCA studies allow practitioners to compare and choose between processes, materials, parts or even product systems The systematic process of an LCA study ensures transparency and repeatability as well as offers a good basis for making decisions Nevertheless, the major strength of the LCA methodology is the ability to identify environmental burden shifting from one compartment to another and, consequently, to provide the "big picture" perspective for the alternative product systems.

However there are also limitations. An initial limitation of the current study is that the data collection only included literature sources and commercial databases and not site-specific data. Furthermore, data collection efforts have been focused on life cycle stages where preliminary calculations or earlier experience indicated that the difference in environmental impacts could be significant. This assumption led to the exclusion of two life cycle stages from the calculations of the life cycle inventory. The current LCA study is valid for only the assumptions presented in this report

It should also be mentioned that the boundary conditions and system definitions have great influence on the study results. Desired results could be achieved by simply choosing the "right" system boundaries. For this reason, the issue of clearly defining and documenting the system boundaries is quite important to an LCA's transparency and credibility.

6.5 Summary

It can be stated that the sub-goals of the thesis, as presented in Chapter 1.4.2, have all been met:

- *Identify the implications of replacing primary aluminum and cast iron with secondary material for the material production phase.*

Four different life cycle scenarios were examined by the LCA study. These scenarios calculate the replacement of primary material by secondary sources resulting from recycling of metal scrap. This sub-objective is discussed in Chapter 6 (this chapter) and Chapter 7.

- *Determine at which stage of the life cycle phases significant environmental emissions occur*

Although the results show that the auto use phase is the dominating contribution to global warming potential and energy consumption, the contribution of the other life cycle stages is also considerable. This sub-objective is discussed in Chapter 6 (this chapter).

- *Examine the role of the Life Cycle Assessment methodology as a tool for identifying the environmental impacts of metal castings at various stages of their life cycle.*

Advantages, disadvantages and limitations of the LCA methodology are discussed in the present Chapter 6.

Chapter 7. Conclusions and Recommendations

In this section, conclusions based on the findings of the study and finally suggestions for future research are presented.

7.1 Conclusions

The research approach of the thesis was to analyse material alternatives for automotive casting applications from a life cycle and interdisciplinary perspective. For this reason, the Life Cycle Assessment methodology has been applied to compare and contrast the environmental life cycle inventory of a suspension component made from aluminium alloy with a similar component made from conventional cast iron.

The initial study (base case scenario) assumed that 100% virgin material was used to produce the two alternative suspension components. Additionally, four different life cycle scenarios have also been examined by the comparative study. These alternative scenarios calculate the replacement of primary material by secondary sources for both product systems.

On the basis of the research work, the major findings of the comparative LCA study are the following:

- ❖ Base Case Scenario for the Aluminium Alloy Suspension Arm:
  - ➢ Global Warming Potential is <u>102 kg CO_2 Equivalents</u>. Major contributors are the Auto Use phase with 52% and the Material Production phase with around 34%.
  - ➢ Energy Consumption is <u>1729 MJ.</u> The Material Production phase contributes 45% and the Auto Use phase 42% of the total amount.

- ❖ Base Case Scenario for the Cast Iron Suspension Arm:
  - ➢ Global Warming Potential is <u>87 kg CO_2 Equivalents</u>. A major contributor is the Auto Use phase with 89%.
  - ➢ Energy Consumption is <u>1209 MJ.</u> The Auto Use phase consumes 86% of the total energy.

- ❖ Alternative Life Cycle Scenarios:
  - ➢ Global Warming Potential <u>is significantly reduced</u> as the percentage of secondary aluminium is increased.
  - ➢ Energy consumption <u>is progressively reduced</u> as the percentage of the secondary aluminium increased within the different life cycle scenarios.

- Global Warming potential <u>is not particularly affected</u> by the percentage change of the secondary cast iron.
- Energy consumption of the cast iron product system <u>is not affected</u> by the percentage change of the secondary cast iron.

- Break-Even Points between the two Product Systems:
  - Base Case Scenario: <u>250,000 km</u>
  - 1st Scenario: <u>200,000 km</u>
  - 2nd Scenario: <u>150,000 km</u>
  - 3rd Scenario: <u>100,000 km</u>
  - 4th Scenario: <u>75,000 km</u>

It becomes evident that the percentage of primary material replaced by secondary sources greatly influences the final overall results. On the one hand cast iron is the material of choice when only primary material is used while on the other hand aluminium is likely to become more environmentally superior as long as secondary material is used.

7.2 Suggestions for Further Research

The entire list of findings builds a solid foundation for understanding and prioritising the significant areas, in terms of potential environmental impacts, for the alternative material groups. These areas could now be targeted more effectively in future research work.

There are also many suggestions for further research and potential extension of the current work. Some of these are the following:

- Although not a compulsory element in the ISO 14040 standards, three additional steps could be applied in the Life Cycle Impacts Assessment (LCIA) phase. These steps include the comparison of the various environmental impact categories against a common reference value (Normalisation), the sorting and ranking of the impact categories in a given hierarchy (Grouping) and, finally, the converting and possible aggregation of the normalised results by using numerical factors (Weighting). However, there is no best available method of how to conduct these extra steps neither is there a recommended set of normalisation factors. Moreover, the weighting factors employ value-choices and are totally subjective.
- More scenario calculations are highly recommended for further studies. These scenarios should not consider only the contribution of secondary material but also examine the implications of wider considerations. For example, the environmental burden of different foundry processes could be compared. Green sand casting vs. shell casting process or pressure die-casting vs. squeeze casting.

- The issue of defining and documenting all the processes and functions of a product system is quite important to an LCA's transparency and credibility. As already mentioned, desired results could be achieved in any LCA study by simply choosing the "right" system boundaries. A possible solution to this problem could be the incorporation of the IDEF0 method within the LCA framework. IDEF0 is a method designed to model the functions and activities of every system or organisation. Functions are described by their inputs, outputs, controls and mechanisms. In general, this modelling method could be used to model and analyse the functional units of a product system and, consequently, define clearly the system boundaries.

Additionally, there are some aspects of the research work that could not be dealt with in any reasonable detail in this thesis. For example, it has not been possible to study in any detail the contribution of the two excluded life cycle stages. Although the study assumed that the manufacturing and assembly and the end-of-life management phases have almost identical industrial processes and could, therefore, be excluded from the calculations, it would be reasonable to examine further the accuracy of this particular assumption.

References

1. Alting Leo, Hauschild Michael and Wenzel Henrik, (1997). *Environmental Assessment of Products Volume 1.* Dordrecht: Kluwer Academic Publishers.
2. Aoki, K., Hayashi, T. and Kumata M. (2001). Reduction of Life Cycle CO_2 Emissions-The Example of Honda Insight. In *Proceedings of the 2001 Environmental Sustainability Conference and Exhibition,* November 2001, Graz, Austria, pp.17-23, paper number 2001-01-3722.
3. Beeley, Peter, (2001). *Foundry Technology* Oxford: Butterworth-Heinemann
4. Bulkley Jonathan, Kar Kristhnendu, Keoleian Gregory, Manion Michelle, (1997). *Industrial Ecology of the Automobile A Life Cycle Perspective.* Society of Automotive Engineers. Warrandale, PA, USA.
5. Commission Recommendation 99/125/EC of 5 February 1999 on the reduction of CO_2 emissions from passenger cars. OJ L 40/49.
6. Costic Mia, Keoleian Gregory, Messick Rebecca, Reppe Peter, (1998). Life Cycle Assessment of a Transmission Case: Magnesium vs. Aluminium. In *1998 SAE International Conference and Exhibition,* February 1998, Detroit, MI, USA, pp. 137-150, paper number 980470.
7. Couslon, G., Stobart, R. (2000). Life-Cycle Analysis and the Fuel Cell Car. In *Proceedings of the 2000 SAE Total Life Cycle Conference,* April 2000, Detroit, MI, USA, pp.157-160, paper number 2000-01-1485.
8. Dahlqvist, E., Wendel, A. (2001). LCA Working Procedures when Developing Environmental Product Declerations for Cars from Volvo. In *Proceedings of the 2001 Environmental Sustainability Conference and Exhibition,* November 2001, Graz, Austria, pp.165-167, paper number 2001-01-3731.
9. Dryzek, John S. (1997). *The Politics of the Earth; Environmental Discourses.* Oxford University Press.
10. EC, (2000). *CO_2 Emissions from Cars. The EU Implementing the Kyoto Protocol.* Luxembourg: European Commission.
11. ENDS, (1999). Electronics take-back: Assessing the effects with LCA. *The ENDS Report.* September 1999, Issue 296.
12. ENDS, (2003). Stainless steel sector gets its sights on sustainability. *The ENDS Report.* April 2003, Issue 339.
13. Energy Saving, (1995). *Energy Saving in Foundry Services.* Department of the Environment. UK
14. European Aluminium Association (EAA), (2003). *Aluminium in the Automotive Industry.* [Online]. Available: http://www.aluminium org/visuals/downloads/auto.pdf
15. European Environmental Agency (EEA), (2002). *Greenhouse Gas Emission Trends and Projections in Europe.* Copenhagen: European Environmental Agency.
16. Finkbeiner, M., Ruhland, K., Cetiner, H. and Stark, B. (2001). Life Cycle Engineering and Design for Environment of the Mercedes-Benz C-Class. In

Proceedings of the 2001 Environmental Sustainability Conference and Exhibition, November 2001, Graz, Austria, pp.157-164, paper number 2001-01-3730.

17. Foti Ross, (2002). Steering the Market Toward Automotive Casting Opportunities. *Engineered Casting Solutions.* Fall 2002, p 33.
18. Foundryman, (1994). *News.* The Foundryman, October 1994, p.338.
19. Fried, W., Hagen, T. and Wörle, G. (2002). Methods and elements towards sustainable products-BMW's strategy in design for recycling and the environment. In *Design and Manufacture for Sustainable Development*, Professional Engineering Publishing, IMechE 2002, pp.13-27.
20. Gibson, T, (2000). Life Cycle Assessment of Advanced Materials for Automotive Applications. In *Proceedings of the 2000 SAE Total Life Cycle Conference*, April 2000, Detroit, MI, USA, pp.161-171, paper number 2000-01-1486.
21. Graedel T.E., Allenby B R , (2003). *Industrial Ecology (Second Edition).* New Jersey: Prentice Hall.
22. Green John, Martchek Kenneth, Pomper Steve, (2000). Credible Life Cycle Inventory Data for Studies of Automotive Aluminium. In *Proceedings of the 2000 SAE Total Life Cycle Conference*, April 2000, Detroit, MI, USA, p.233.
23. Handbook, (2002). *Handbook on Life Cycle Assessment.* Center of Environmental Science – Leiden University. Dordrecht: Kluwer Academic Publishers
24. Happian-Smith, Julian, (2001). *An Introduction to Modern Vehicle Design* Oxford: Butterworth-Heinemann.
25. Intergovernmental Panel on Climate Change (IPCC), (1996). *Climate Change 1995. The Science of Climate Change.* London: Cambridge University Press.
26. ISO 14040, (1997). *Environmental Management: Life Cycle Assessment· Principles and framework.* Geneva: International Organization for Standardization.
27. Jenssen Christian, Thiel Georg, (2000). Comparative Life Cycle Assessment of Aluminium and Steel Bumper Carriers. In *Proceedings of the 2000 SAE Total Life Cycle Conference*, April 2000, Detroit, MI, USA, pp.225-231, paper number 2000-01-1495
28. Kalpakjan, Serope, (2001). *Manufacturing Engineering and Technology.* New Jersey: Prentice Hall.
29. Lessiter, Michael, (2000). *Engineered Cast Components for the Automotive Industry.* Engineered Casting Solutions, Fall 2000, p.37.
30. Mass Balance, (2003). *The Foundry Mass Balance Project.* Casting Technology International. UK
31. Moore C.M., Rohrig, K. and Deike, R., (1999). *Auto Aluminium is it really Cost Effective?* Foundry Trade Journal International, vv, p.37.
32. Non-Ferrous Foundries, (1997). *Energy Consumption Guide: Non-ferrous Foundries (Second Edition).* Department of the Environment. UK
33. Partnership for a New Generation of Vehicles (PNGV), (2003). [Online]. Available· http://www.uscar.org/pngv/

34. Peterson, P, (2002). Environment for Green Vehicles, Efficient is Better. In *Designing and Achieving Lightweight Vehicles*. SAE, S-P 1684, pp.11-15.

35. Roth, R, Kelkar, A. and Clark, J, (2001). Automotive Bodies: Can Aluminium Be an Economical Alternative to Steel? In *Journal of Metals (JOM)*, August 2001, pp.28-32.

36. SAE, (2001). *Society of Automotive Engineers (SAE) Handbook and Standards on CD-ROM.* Warrandale: SAE Electronic Publications.

37. Saur, K., Fava, J. A. and Spatari, S, (2000). Life Cycle Engineering Case Study: Automobile Fender Designs. In *Environmental Progress*. Vol. 19, No 2, pp.72-82.

38. Stephens, R., Wheeler C. and Pryor M. (2001). Life Cycle Assessment of Aluminium Casting Processes. In *Proceedings of the 2001 Environmental Sustainability Conference and Exhibition*, November 2001, Graz, Austria, pp.115-140, paper number 2001-01-3726.

39. Sullivan, J., Cobas-Flores, E. (2001). Full Vehicle LCA's: A Review. In *Proceedings of the 2001 Environmental Sustainability Conference and Exhibition*, November 2001, Graz, Austria, pp.99-114, paper number 2001-01-3725.

40. Sustainable Industry, (1998). *Sustainable Industry· Metal Casting Industry Profile*. [Online]. Available: http://www sectorstar.org/sector/MetalCasting/BackgroundDocuments cfm?DocID=63

41. ULSAB-Advanced Vehicle Concepts (AVC), (2003). [Online]. Available: http://www.worldautosteel com/

42. UNEP, (2002). *UNEP Report on the Automotive Industry as a Partner on Sustainable Development.* Geneva: United Nations Environment Programme.

Appendix I

The Life Cycle Inventory (LCI) results of the base case scenario for the aluminium suspension arm are illustrated in the following pages. The results are presented in printouts from the LCA software tool Boustead 4 4 Model, which used to conduct the calculations.

Code 6019 ALUMINIUM SUSPENSION ARM
Gross data per kg

GROSS ENERGY/MJ
Totals may not agree because of rounding

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Elec	456 17	246 08	1 82	0 01	704 08
Oil	83 82	730 09	16 43	99 52	929.85
Other	8 49	85 89	0 21	0 97	95 56
Total	548 48	1062.06	18 46	100 50	1729 50

PRIMARY FUELS & FEEDSTOCKS/MJ
Totals may not agree because of rounding

	Fuel production	Fuel use	Transport fuels	Feedstock	Total
Coal (use)	140 08	83 71	0 31	<0 01	224 09
Oil (use)	78 50	739 55	17 89	99 52	935 46
Gas (use)	115 65	119.19	0 13	0 01	234 99
Hydro (use)	105 32	63 15	<0 01	-	168 47
Nuclear (use)	107 80	56 06	0.13	-	163 99
Lignite (use)	0 78	0 36	<0 01	-	1 14
Wood (use)	-	-	-	<0 01	<0 01
Sulphur (use)	<0 01	<0 01	<0 01	0 97	0 97
Biomass (use)	0 19	0 10	<0 01	<0 01	0 28
Hydrogen (use)	<0 01	0 36	<0 01	-	0 36
Recovered energy (use)	<0 01	-0 51	<0 01	-	-0 51
Unspecified (use)	0 13	0 07	<0 01	-	0 20
Peat (use)	0 02	0 01	<0 01	-	0 03
Geothermal (use)	<0 01	<0 01	<0 01	-	<0 01
Solar (use)	<0 01	<0 01	<0 01	-	<0 01
Wave/tidal (use)	0 01	<0 01	<0 01	-	0 01
Totals	548 48	1,062 06	18 46	100 50	1,729 50

FUELS & FEEDSTOCKS (in mg)

Crude oil	20,787,882
Gas/condensate .	4,342,400
Coal ..	8,002,339
Metallurgical coal	3,684
Lignite..	75,537
Peat	3,860
Wood (50% water)	2

OTHER RAW MATERIALS INPUTS/mg

Fe	9,143	Zn	3	fluorspar	247,791
Mg	39,486	air	1,587,304	gravel	34
Mn	39,486	barytes	6	limestone (CaCO3)	152,222
N2	819	bauxite	13,649,249	olivine	86
O2	182	bentonite	7	potassium chloride (KCl)	1,413
Pb	70	biomass (including water)	32,156	sand (SiO2)	192,008
S (bonded)	119	dolomite	112	sodium chloride (NaCl)	121,690
S (elemental)	104,477	ferromanganese	8		

Printout date 13/11/2003
Printout time 13 41 07

continued

Code 6019 ALUMINIUM SUSPENSION ARM
Gross data per kg

continued

AIR EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
Dust	108,692	52,729	595	4,414	-	166,430
CO	16,566	466,503	5,918	695	-	489,681
CO2	33,766,175	57,642,963	1,202,382	4,487,982	-33,058	97,066,444
SOX	332,783	209,903	13,978	5,233	-	561,897
NOX	183,744	654,848	9,938	4,793	-	853,324
N2O	<1	<1	-	-	-	<1
Hydrocarbons	41,085	159,527	2,838	1,317	-	204,767
Methane	144,349	45,365	-	1	-	189,715
H2S	<1	-	-	<1	-	1
HCl	4,250	233	-	<1	-	4,483
Cl2	-	-	-	35	-	35
HF	265	9	-	1	-	275
Lead(Pb)	-	<1	-	<1	-	<1
Metals	26	66	-	<1	-	93
F2	-	-	-	217	-	217
Mercaptans	-	1	-	<1	-	1
Organo-Cl	-	-	-	<1	-	<1
Aromatic-HC	-	-	-	19	-	19
Polycyclic-HC	-	-	-	<1	-	<1
Other organics	-	-	-	<1	-	<1
CFC/HCFC	-	-	-	<1	-	<1
Aldehydes (CHO)	-	-	-	<1	-	<1
HCN	-	-	-	<1	-	<1
H2SO4	-	-	-	<1	-	<1
Hydrogen (H2)	<1	-	-	55	-	56
Mercury (Hg)	-	-	-	<1	-	<1
Ammonia (NH3)	-	-	-	3	-	3
CS2	-	-	-	<1	-	<1
DCE	-	-	-	<1	-	<1
VCM	-	-	-	<1	-	<1
VOC	-	-	-	<1	-	<1
Cu (process)	-	-	-	<1	-	<1
Cd (process)	-	-	-	<1	-	<1
Zn (process)	-	-	-	<1	-	<1
Sb (process)	-	-	-	<1	-	<1

CO2 EQUIVALENTS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equivalent	41,882,830	61,116,413	1,214,217	4,489,447	-33,058	108,669,848
100 year equivalent	36,830,628	59,528,640	1,214,217	4,489,400	-33,058	102,029,827
500 year equivalent	34,737,573	58,870,845	1,214,217	4,489,381	-33,058	99,278,958

SOLID WASTE/mg	Fuel prod'n	Fuel use	Transport	Process	Total
Mineral	1,513,946	-	-	20,974,190	22,488,135
Mixed industrial	93,260	-	-	9,551	102,811
Slags/ash	429,033	34,915	-	294,430	758,377
Inert chemical	<1	-	-	6,199	6,200
Regulated chemical	<1	-	-	46	46
Unspecified	<1	-	-	<1	<1
Construction	-	-	-	<1	<1
Metals	-	-	-	4	4
To incinerator	-	-	-	4	4
Plastic containers	-	-	-	<1	<1
Paper & board	-	-	-	<1	<1
Plastics	-	-	-	1	1
Putrescibles	-	-	-	2	2
Wood waste	-	-	-	<1	<1
Wooden pallets	-	-	-	<1	<1
To recycling	-	-	-	<1	<1
Waste returned to mine	-	-	-	230	230
Tailings	-	-	-	242	242

Printout date 13/11/2003
Printout time 13 41 07

continued

Code 6019 ALUMINIUM SUSPENSION ARM
Gross data per kg
continued

WATER EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Total
COD	1,071	-	-	8	1,079
BOD	933	-	-	<1	933
Acid (H+)	54	-	-	174	228
Dissolved solids	<1	-	-	544	544
Hydrocarbons	933	<1	-	<1	933
NH4	48	-	-	<1	48
Suspended solids	2,267	-	-	720,801	723,068
Phenol	933	-	-	<1	933
Al+++	-	-	-	<1	<1
Ca++	-	-	-	5	5
Cu++/Cu+++	-	-	-	<1	<1
Fe++/Fe+++	-	-	-	<1	<1
Hg	-	-	-	<1	<1
Pb	-	-	-	<1	<1
Mg++	-	-	-	<1	<1
Na+	-	-	-	225,329	225,329
K+	-	-	-	44	44
Ni++	-	-	-	<1	<1
Zn++	-	-	-	<1	<1
Other metals	13	-	-	43	56
NO3-	-	-	-	1	1
Other nitrogen	12	-	-	<1	12
BrO3-	-	-	-	<1	<1
CrO3--	-	-	-	<1	<1
Cl-	-	-	-	1,680	1,680
ClO3-	-	-	-	23	23
CN-	-	-	-	<1	<1
F-	-	-	-	7,018	7,018
SO4--	-	-	-	560	560
CO3--	-	-	-	7	7
Phosphate as P2O5	-	-	-	<1	<1
AOX	-	-	-	<1	<1
TOC	-	-	-	<1	<1
Arsenic	-	-	-	<1	<1
DCE	-	-	-	<1	<1
VCM	-	-	-	<1	<1
Detergent/oil	-	-	-	<1	<1
Dissolved Cl2	-	-	-	<1	<1
Organo-chlorine	-	-	-	<1	<1
Dissolved organics	-	-	-	<1	<1
Other organics	-	-	-	<1	<1
Sulphur/sulphide	-	-	-	<1	<1
Cd++	-	-	-	<1	<1
Mn++	-	-	-	<1	<1

WATER USE (in mg)

Source	Use in Process	Use in Cooling	Totals
Public supply	168,168,711	-	168,168,711
River/canal	209	95,588	95,797
Sea	2,838	91,694	94,532
Unspecified	17,666,742	73,757	17,740,498
Well	72	1,502	1,574
Totals	185,838,571	262,541	186,101,112

Total cooling water reported in recirculating systems = 75

Printout date 13/11/2003
Printout time: 13 41 07

Appendix II

The LCI results of the 1st Scenario for the aluminium alloy suspension arm are illustrated in the following pages. The results are presented in printouts from the LCA software tool Boustead 4.4 Model.

Code 6215 ALUMINIUM 1ST SCENARIO (75/25)
Gross data per kg

GROSS ENERGY/MJ
Totals may not agree because of rounding

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Elec	370 01	195 89	1 48	0 00	567 37
Oil	79 40	713 49	13 57	74 41	880 87
Other	7 47	73 08	0 20	0.73	81.47
Total	456.88	982 45	15.25	75 14	1529 72

PRIMARY FUELS & FEEDSTOCKS/MJ
Totals may not agree because of rounding

	Fuel production	Fuel use	Transport fuels	Feedstock	Total
Coal (use)	116 57	70 17	0 26	<0 01	187 00
Oil (use)	72 23	721 18	14 77	74.41	882 59
Gas (use)	98 74	97 94	0 11	0 01	196 80
Hydro (use)	78 97	47 30	<0 01	-	126.27
Nuclear (use)	89 50	45 55	0.10	-	135.15
Lignite (use)	0 59	0 28	<0.01	-	0.87
Wood (use)	-	-	-	<0 01	<0 01
Sulphur (use)	<0 01	<0 01	<0 01	0 72	0 72
Biomass (use)	0 15	0 08	<0 01	<0 01	0 23
Hydrogen (use)	<0 01	0 27	<0.01	-	0 27
Recovered energy (use)	<0 01	-0 38	<0 01	-	-0 38
Unspecified (use)	0 10	0 05	<0 01	-	0 16
Peat (use)	0 02	0 01	<0 01	-	0 03
Geothermal (use)	<0.01	<0 01	<0.01	-	<0 01
Solar (use)	<0.01	<0 01	<0 01	-	<0 01
Wave/tidal (use)	0 01	<0 01	<0 01	-	0 01
Totals	456 88	982 45	15 25	75 14	1,529 72

FUELS & FEEDSTOCKS (in mg)	
Crude oil..	19,613,122
Gas/condensate. .	3,636,663
Coal	6,677,626
Metallurgical coal	3,221
Lignite	57,341
Peat. .	3,182
Wood (50% water).	1

OTHER RAW MATERIALS INPUTS/mg

Fe	7,994	Zn	2	fluorspar	185,265
Mg	29,522	air	1,186,853	gravel	29
Mn	29,522	barytes	5	limestone (CaCO3)	114,053
N2	701	bauxite	10,205,090	olivine	75
O2	157	bentonite	6	potassium chloride (KCl)	1,056
Pb	61	biomass (including water)	26,445	sand (SiO2)	192,006
S (bonded)	89	dolomite	98	sodium chloride (NaCl)	91,004
S (elemental)	78,119	ferromanganese	7		

Printout date 13/11/2003
Printout time 13 43 53

continued

Code 6215 ALUMINIUM 1ST SCENARIO (75/25)
Gross data per kg

continued

AIR EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
Dust	89,901	51,434	513	-49,683	-	92,165
CO	13,969	466,209	5,222	545	-	485,945
CO2	28,618,996	55,722,678	987,388	3,356,589	-27,192	88,658,459
SOX	284,943	188,863	10,835	3,913	-	488,554
NOX	153,637	638,629	8,427	3,584	-	804,277
N2O	<1	<1	-	-	-	<1
Hydrocarbons	37,024	157,862	2,397	985	-	198,268
Methane	120,836	38,608	-	1	-	159,446
H2S	<1	-	-	<1	-	<1
HCl	3,501	233	-	<1	-	3,734
Cl2	-	-	-	26	-	26
HF	218	9	-	1	-	228
Lead(Pb)	-	<1	-	<1	-	<1
Metals	22	50	-	<1	-	71
F2	-	-	-	162	-	162
Mercaptans	-	<1	-	<1	-	<1
Organo-Cl	-	-	-	<1	-	<1
Aromatic-HC	-	-	-	16	-	16
Polycyclic-HC	-	-	-	<1	-	<1
Other organics	-	-	-	<1	-	<1
CFC/HCFC	-	-	-	<1	-	<1
Aldehydes (CHO)	-	-	-	<1	-	<1
HCN	-	-	-	<1	-	<1
H2SO4	-	-	-	<1	-	<1
Hydrogen (H2)	<1	-	-	41	-	42
Mercury (Hg)	-	-	-	<1	-	<1
Ammonia (NH3)	-	-	-	2	-	2
CS2	-	-	-	<1	-	<1
DCE	-	-	-	<1	-	<1
VCM	-	-	-	<1	-	<1
VOC	-	-	-	<1	-	<1
Cu (process)	-	-	-	<1	-	<1
Cd (process)	-	-	-	<1	-	<1
Zn (process)	-	-	-	<1	-	<1
Sb (process)	-	-	-	<1	-	<1

CO2 EQUIVALENTS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equivalent	35,413,773	58,817,173	997,833	3,357,735	-27,192	98,559,323
100 year equivalent	31,184,499	57,465,878	997,833	3,357,700	-27,192	92,978,718
500 year equivalent	29,432,371	56,906,054	997,833	3,357,685	-27,192	90,666,750

SOLID WASTE/mg	Fuel prod'n	Fuel use	Transport	Process	Total
Mineral	1,262,366	-	-	15,688,004	16,950,370
Mixed industrial	87,991	-	-	7,177	95,168
Slags/ash	353,608	34,886	-	220,486	608,980
Inert chemical	<1	-	-	4,636	4,636
Regulated chemical	<1	-	-	35	35
Unspecified	<1	-	-	<1	<1
Construction	-	-	-	<1	<1
Metals	-	-	-	3	3
To incinerator	-	-	-	3	3
Plastic containers	-	-	-	<1	<1
Paper & board	-	-	-	<1	<1
Plastics	-	-	-	<1	<1
Putrescibles	-	-	-	2	2
Wood waste	-	-	-	<1	<1
Wooden pallets	-	-	-	<1	<1
To recycling	-	-	-	<1	<1
Waste returned to mine	-	-	-	201	201
Tailings	-	-	-	212	212

Printout date 13/11/2003
Printout time 13 43 54

continued .

Code 6215 ALUMINIUM 1ST SCENARIO (75/25)
Gross data per kg
continued ...

WATER EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Total
COD	1,012	-	-	7	1,019
BOD	880	-	-	<1	880
Acid (H+)	54	-	-	130	184
Dissolved solids	<1	-	-	407	407
Hydrocarbons	880	<1	-	<1	880
NH4	48	-	-	<1	48
Suspended solids	1,898	-	-	539,013	540,911
Phenol	880	-	-	<1	880
Al+++	-	-	-	<1	<1
Ca++	-	-	-	3	3
Cu++/Cu+++	-	-	-	<1	<1
Fe++/Fe+++	-	-	-	<1	<1
Hg	-	-	-	<1	<1
Pb	-	-	-	<1	<1
Mg++	-	-	-	<1	<1
Na+	-	-	-	168,475	168,475
K+	-	-	-	33	33
Ni++	-	-	-	<1	<1
Zn++	-	-	-	<1	<1
Other metals	13	-	-	32	45
NO3-	-	-	-	1	1
Other nitrogen	12	-	-	<1	12
BrO3-	-	-	-	<1	<1
CrO3--	-	-	-	<1	<1
Cl-	-	-	-	1,256	1,256
ClO3-	-	-	-	17	17
CN-	-	-	-	<1	<1
F-	-	-	-	5,247	5,247
SO4--	-	-	-	419	419
CO3--	-	-	-	5	5
Phosphate as P2O5	-	-	-	<1	<1
AOX	-	-	-	<1	<1
TOC	-	-	-	<1	<1
Arsenic	-	-	-	<1	<1
DCE	-	-	-	<1	<1
VCM	-	-	-	<1	<1
Detergent/oil	-	-	-	<1	<1
Dissolved Cl2	-	-	-	<1	<1
Organo-chlorine	-	-	-	<1	<1
Dissolved organics	-	-	-	<1	<1
Other organics	-	-	-	<1	<1
Sulphur/sulphide	-	-	-	<1	<1
Cd++	-	-	-	<1	<1
Mn++	-	-	-	<1	<1

WATER USE (in mg)

Source	Use in Process	Use in Cooling	Totals
Public supply	132,983,821	-	132,983,821
River/canal	182	71,513	71,695
Sea	2,178	73,818	75,997
Unspecified	14,741,773	55,687	14,797,460
Well	59	1,123	1,183
Totals	147,728,014	202,141	147,930,155

Total cooling water reported in recirculating systems = 56

Printout date 13/11/2003
Printout time. 13 43 54

Appendix III

The LCI results of the 2nd Scenario for the aluminium alloy suspension arm are presented in the following pages. The results are presented in printouts from the LCA software tool Boustead 4.4 Model.

Code 6036 ALUMINIUM 2ND SCENARIO (50/50)
Gross data per kg

GROSS ENERGY/MJ
Totals may not agree because of rounding

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Elec	285.43	146.62	1.14	0.00	433.20
Oil	75.07	697.20	10.77	49.76	832.80
Other	6.48	60.50	0.18	0.49	67.64
Total	366.98	904.32	12.09	50.25	1333.64

PRIMARY FUELS & FEEDSTOCKS/MJ
Totals may not agree because of rounding

	Fuel production	Fuel use	Transport fuels	Feedstock	Total
Coal (use)	93.50	56.88	0.21	<0.01	150.59
Oil (use)	66.09	703.14	11.71	49.76	830.71
Gas (use)	82.14	77.09	0.09	0.01	159.31
Hydro (use)	53.10	31.75	<0.01	-	84.85
Nuclear (use)	71.54	35.23	0.08	-	106.84
Lignite (use)	0.41	0.19	<0.01	-	0.60
Wood (use)	-	-	-	<0.01	<0.01
Sulphur (use)	<0.01	<0.01	<0.01	0.48	0.48
Biomass (use)	0.12	0.06	<0.01	<0.01	0.18
Hydrogen (use)	<0.01	0.18	<0.01	-	0.18
Recovered energy (use)	<0.01	-0.25	<0.01	-	-0.25
Unspecified (use)	0.08	0.04	<0.01	-	0.12
Peat (use)	0.01	0.01	<0.01	-	0.02
Geothermal (use)	<0.01	<0.01	<0.01	-	<0.01
Solar (use)	<0.01	<0.01	<0.01	-	<0.01
Wave/tidal (use)	<0.01	<0.01	<0.01	-	0.01
Totals	366.98	904.32	12.09	50.25	1,333.64

FUELS & FEEDSTOCKS (in mg)

Crude oil	18,460,091
Gas/condensate.. ...	2,943,981
Coal	5,377,416
Metallurgical coal	2,767
Lignite	39,482
Peat...... .	2,516
Wood (50% water) . .	-

OTHER RAW MATERIALS INPUTS/mg

Fe	6,867	Zn	2	fluorspar	123,896
Mg	19,743	air	793,808	gravel	25
Mn	19,743	barytes	4	limestone (CaCO3)	76,591
N2	585	bauxite	6,824,641	olivine	64
O2	131	bentonite	5	potassium chloride (KCl)	706
Pb	53	biomass (including water)	20,838	sand (SiO2)	192,004
S (bonded)	60	dolomite	84	sodium chloride (NaCl)	60,885
S (elemental)	52,248	ferromanganese	6		

Printout date 13/11/2003
Printout time: 13.44.07

continued

Code 6036 ALUMINIUM 2ND SCENARIO (50/50)
Gross data per kg

continued ...

AIR EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
Dust	71,458	50,162	433	-102,780	-	19,273
CO	11,420	465,920	4,540	397	-	482,278
CO2	23,567,029	53,837,914	776,371	2,246,124	-21,434	80,406,004
SOX	237,988	168,212	7,750	2,617	-	416,567
NOX	124,086	622,710	6,945	2,397	-	756,138
N2O	<1	<1	-	-	-	<1
Hydrocarbons	33,038	156,228	1,965	659	-	191,890
Methane	97,759	31,977	-	<1	-	129,737
H2S	<1	-	-	<1	-	<1
HCl	2,765	233	-	<1	-	2,998
Cl2	-	-	-	18	-	18
HF	172	9	-	<1	-	182
Lead(Pb)	-	<1	-	<1	-	<1
Metals	17	33	-	<1	-	51
F2	-	-	-	108	-	108
Mercaptans	-	<1	-	<1	-	<1
Organo-Cl	-	-	-	<1	-	<1
Aromatic-HC	-	-	-	14	-	14
Polycyclic-HC	-	-	-	<1	-	<1
Other organics	-	-	-	<1	-	<1
CFC/HCFC	-	-	-	<1	-	<1
Aldehydes (CHO)	-	-	-	<1	-	<1
HCN	-	-	-	<1	-	<1
H2SO4	-	-	-	<1	-	<1
Hydrogen (H2)	<1	-	-	28	-	28
Mercury (Hg)	-	-	-	<1	-	<1
Ammonia (NH3)	-	-	-	1	-	1
CS2	-	-	-	<1	-	<1
DCE	-	-	-	<1	-	<1
VCM	-	-	-	<1	-	<1
VOC	-	-	-	<1	-	<1
Cu (process)	-	-	-	<1	-	<1
Cd (process)	-	-	-	<1	-	<1
Zn (process)	-	-	-	<1	-	<1
Sb (process)	-	-	-	<1	-	<1

CO2 EQUIVALENTS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equivalent	29,064,379	56,560,465	785,451	2,246,958	-21,434	88,635,819
100 year equivalent	25,642,810	55,441,273	785,451	2,246,933	-21,434	84,095,034
500 year equivalent	24,225,303	54,977,606	785,451	2,246,923	-21,434	82,213,850

SOLID WASTE/mg	Fuel prod'n	Fuel use	Transport	Process	Total
Mineral	1,015,441	-	-	10,499,601	11,515,041
Mixed industrial	82,819	-	-	4,846	87,666
Slags/ash	279,578	34,857	-	147,911	462,345
Inert chemical	<1	-	-	3,102	3,102
Regulated chemical	<1	-	-	23	23
Unspecified	<1	-	-	<1	<1
Construction	-	-	-	<1	<1
Metals	-	-	-	2	2
To incinerator	-	-	-	3	3
Plastic containers	-	-	-	<1	<1
Paper & board	-	-	-	<1	<1
Plastics	-	-	-	<1	<1
Putrescibles	-	-	-	2	2
Wood waste	-	-	-	<1	<1
Wooden pallets	-	-	-	<1	<1
To recycling	-	-	-	<1	<1
Waste returned to mine	-	-	-	173	173
Tailings	-	-	-	182	182

Printout date 13/11/2003
Printout time 13 44 07

continued

Code. 6036 ALUMINIUM 2ND SCENARIO (50/50)
Gross data per kg
continued

WATER EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Total
COD	955	-	-	6	960
BOD	828	-	-	<1	828
Acid (H+)	53	-	-	87	140
Dissolved solids	<1	-	-	272	272
Hydrocarbons	828	<1	-	<1	829
NH4	47	-	-	<1	48
Suspended solids	1,537	-	-	360,588	362,124
Phenol	828	-	-	<1	828
Al+++	-	-	-	<1	<1
Ca++	-	-	-	2	2
Cu++/Cu+++	-	-	-	<1	<1
Fe++/Fe+++	-	-	-	<1	<1
Hg	-	-	-	<1	<1
Pb	-	-	-	<1	<1
Mg++	-	-	-	<1	<1
Na+	-	-	-	112,673	112,673
K+	-	-	-	22	22
Ni++	-	-	-	<1	<1
Zn++	-	-	-	<1	<1
Other metals	13	-	-	22	35
NO3-	-	-	-	<1	<1
Other nitrogen	12	-	-	<1	12
BrO3-	-	-	-	<1	<1
CrO3--	-	-	-	<1	<1
Cl-	-	-	-	841	841
ClO3-	-	-	-	12	12
CN-	-	-	-	<1	<1
F-	-	-	-	3,509	3,509
SO4--	-	-	-	280	280
CO3--	-	-	-	3	3
Phosphate as P2O5	-	-	-	<1	<1
AOX	-	-	-	<1	<1
TOC	-	-	-	<1	<1
Arsenic	-	-	-	<1	<1
DCE	-	-	-	<1	<1
VCM	-	-	-	<1	<1
Detergent/oil	-	-	-	<1	<1
Dissolved Cl2	-	-	-	<1	<1
Organo-chlorine	-	-	-	<1	<1
Dissolved organics	-	-	-	<1	<1
Other organics	-	-	-	<1	<1
Sulphur/sulphide	-	-	-	<1	<1
Cd++	-	-	-	<1	<1
Mn++	-	-	-	<1	<1

WATER USE (in mg)

Source	Use in Process	Use in Cooling	Totals
Public supply	98,449,774	-	98,449,774
River/canal	156	47,882	48,039
Sea	1,531	56,273	57,804
Unspecified	11,870,910	37,952	11,908,861
Well	47	752	799
Totals	110,322,417	142,860	110,465,276

Total cooling water reported in recirculating systems = 38

Printout date: 13/11/2003
Printout time 13 44 07

Appendix IV

The LCI results of the 3rd Scenario for the aluminium alloy suspension arm are illustrated in the following pages. The results are presented in printouts from the LCA software tool Boustead 4.4 Model.

Code. 6235 ALUMINIUM 3RD SCENARIO (25/75)
Gross data per kg

GROSS ENERGY/MJ

Totals may not agree because of rounding

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Elec	197.58	95.44	0.79	0.00	293.81
Oil	70.57	680.27	7.86	24.16	782.86
Other	5.44	47.43	0.17	0.24	53.28
Total	273.59	823.14	8.81	24.40	1129.95

PRIMARY FUELS & FEEDSTOCKS/MJ

Totals may not agree because of rounding

	Fuel production	Fuel use	Transport fuels	Feedstock	Total
Coal (use)	69.52	43.08	0.16	<0.01	112.76
Oil (use)	59.70	684.41	8.54	24.16	776.80
Gas (use)	64.89	55.42	0.06	0.01	120.37
Hydro (use)	26.23	15.60	<0.01	-	41.82
Nuclear (use)	52.87	24.50	0.06	-	77.43
Lignite (use)	0.22	0.10	<0.01	-	0.32
Wood (use)	-	-	-	<0.01	<0.01
Sulphur (use)	<0.01	<0.01	<0.01	0.23	0.23
Biomass (use)	0.09	0.04	<0.01	<0.01	0.13
Hydrogen (use)	<0.01	0.09	<0.01	-	0.09
Recovered energy (use)	<0.01	-0.12	<0.01	-	-0.12
Unspecified (use)	0.06	0.03	<0.01	-	0.08
Peat (use)	0.01	0.01	<0.01	-	0.02
Geothermal (use)	<0.01	<0.01	<0.01	-	<0.01
Solar (use)	<0.01	<0.01	<0.01	-	<0.01
Wave/tidal (use)	<0.01	<0.01	<0.01	-	<0.01
Totals	273.59	823.14	8.81	24.40	1,129.95

FUELS & FEEDSTOCKS (in mg)

Crude oil .. .	17,262,283
Gas/condensate	2,224,398
Coal ..	4,026,713
Metallurgical coal	2,295
Lignite ..	20,928
Peat . .	1,825
Wood (50% water) .	-

OTHER RAW MATERIALS INPUTS/mg

Fe	5,695	Zn	2	fluorspar	60,143
Mg	9,584	air	385,500	gravel	21
Mn	9,584	barytes	3	limestone ($CaCO_3$)	37,673
N_2	465	bauxite	3,312,912	olivine	53
O_2	105	bentonite	4	potassium chloride (KCl)	343
Pb	44	biomass (including water)	15,014	sand (SiO_2)	192,002
S (bonded)	29	dolomite	70	sodium chloride (NaCl)	29,597
S (elemental)	25,372	ferromanganese	5		

Printout date 13/11/2003
Printout time 13.44.27

continued ..

Code 6235 ALUMINIUM 3RD SCENARIO (25/75)
Gross data per kg

continued .

AIR EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
Dust	52,298	48,841	350	-157,938	-	-56,450
CO	8,772	465,620	3,832	244	-	478,468
CO2	18,318,869	51,879,955	557,159	1,092,534	-15,452	71,833,064
SOX	189,210	146,760	4,546	1,270	-	341,785
NOX	93,388	606,173	5,404	1,164	-	706,130
N2O	<1	<1	-	-	-	<1
Hydrocarbons	28,896	154,530	1,517	320	-	185,264
Methane	73,786	25,088	-	<1	-	98,874
H2S	<1	-	-	<1	-	<1
HCl	2,001	232	-	<1	-	2,234
Cl2	-	-	-	9	-	9
HF	125	9	-	<1	-	134
Lead(Pb)	-	<1	-	<1	-	<1
Metals	12	16	-	<1	-	29
F2	-	-	-	53	-	53
Mercaptans	-	<1	-	<1	-	<1
Organo-Cl	-	-	-	<1	-	<1
Aromatic-HC	-	-	-	12	-	12
Polycyclic-HC	-	-	-	<1	-	<1
Other organics	-	-	-	<1	-	<1
CFC/HCFC	-	-	-	<1	-	<1
Aldehydes (CHO)	-	-	-	<1	-	<1
HCN	-	-	-	<1	-	<1
H2SO4	-	-	-	<1	-	<1
Hydrogen (H2)	<1	-	-	14	-	14
Mercury (Hg)	-	-	-	<1	-	<1
Ammonia (NH3)	-	-	-	<1	-	<1
CS2	-	-	-	<1	-	<1
DCE	-	-	-	<1	-	<1
VCM	-	-	-	<1	-	<1
VOC	-	-	-	<1	-	<1
Cu (process)	-	-	-	<1	-	<1
Cd (process)	-	-	-	<1	-	<1
Zn (process)	-	-	-	<1	-	<1
Sb (process)	-	-	-	<1	-	<1

CO2 EQUIVALENTS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equivalent	22,468,407	54,216,117	564,822	1,093,044	-15,452	78,326,938
100 year equivalent	19,885,911	53,338,042	564,822	1,093,030	-15,452	74,866,353
500 year equivalent	18,816,020	52,974,267	564,822	1,093,024	-15,452	73,432,681

SOLID WASTE/mg	Fuel prod'n	Fuel use	Transport	Process	Total
Mineral	758,926	-	-	5,109,706	5,868,632
Mixed industrial	77,447	-	-	2,425	79,872
Slags/ash	202,673	34,827	-	72,517	310,017
Inert chemical	<1	-	-	1,508	1,508
Regulated chemical	<1	-	-	11	11
Unspecified	<1	-	-	<1	<1
Construction	-	-	-	<1	<1
Metals	-	-	-	1	1
To incinerator	-	-	-	2	2
Plastic containers	-	-	-	<1	<1
Paper & board	-	-	-	<1	<1
Plastics	-	-	-	<1	<1
Putrescibles	-	-	-	1	1
Wood waste	-	-	-	<1	<1
Wooden pallets	-	-	-	<1	<1
To recycling	-	-	-	<1	<1
Waste returned to mine	-	-	-	144	144
Tailings	-	-	-	151	151

Printout date 13/11/2003
Printout time 13 44 27

continued

Code 6235 ALUMINIUM 3RD SCENARIO (25/75)
Gross data per kg
continued

WATER EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Total
COD	895	-	-	4	899
BOD	774	-	-	<1	775
Acid (H+)	53	-	-	42	95
Dissolved solids	<1	-	-	132	132
Hydrocarbons	774	<1	-	<1	775
NH4	47	-	-	<1	47
Suspended solids	1,161	-	-	175,233	176,394
Phenol	774	-	-	<1	774
Al+++	-	-	-	<1	<1
Ca++	-	-	-	1	1
Cu++/Cu+++	-	-	-	<1	<1
Fe++/Fe+++	-	-	-	<1	<1
Hg	-	-	-	<1	<1
Pb	-	-	-	<1	<1
Mg++	-	-	-	<1	<1
Na+	-	-	-	54,703	54,703
K+	-	-	-	11	11
Ni++	-	-	-	<1	<1
Zn++	-	-	-	<1	<1
Other metals	13	-	-	11	23
NO3-	-	-	-	<1	<1
Other nitrogen	12	-	-	<1	12
BrO3-	-	-	-	<1	<1
CrO3--	-	-	-	<1	<1
Cl-	-	-	-	409	409
ClO3-	-	-	-	6	6
CN-	-	-	-	<1	<1
F-	-	-	-	1,703	1,703
SO4--	-	-	-	136	136
CO3--	-	-	-	2	2
Phosphate as P2O5	-	-	-	<1	<1
AOX	-	-	-	<1	<1
TOC	-	-	-	<1	<1
Arsenic	-	-	-	<1	<1
DCE	-	-	-	<1	<1
VCM	-	-	-	<1	<1
Detergent/oil	-	-	-	<1	<1
Dissolved Cl2	-	-	-	<1	<1
Organo-chlorine	-	-	-	<1	<1
Dissolved organics	-	-	-	<1	<1
Other organics	-	-	-	<1	<1
Sulphur/sulphide	-	-	-	<1	<1
Cd++	-	-	-	<1	<1
Mn++	-	-	-	<1	<1

WATER USE (in mg)

Source	Use in Process	Use in Cooling	Totals
Public supply	62,574,598	-	62,574,598
River/canal	129	23,334	23,464
Sea	858	38,047	38,904
Unspecified	8,888,557	19,528	8,908,084
Well	34	367	400
Totals	71,464,175	81,275	71,545,450

Total cooling water reported in recirculating systems = 18

Printout date 13/11/2003
Printout time 13 44 27

Appendix V

The LCI results of the 4th Scenario for the aluminium alloy suspension arm are presented in the following pages. The results are presented in printouts from the LCA software tool Boustead 4.4 Model.

Code 6255 ALUMINIUM 4TH SCENARIO (SECONDARY)
Gross data per kg

GROSS ENERGY/MJ
Totals may not agree because of rounding

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Elec	114 69	47.16	0 46	0 00	162 31
Oil	66 32	664 31	5 11	0 01	735 75
Other	4 47	35 10	0 16	0 00	39 72
Total	185.48	746 57	5 72	0 01	937 79

PRIMARY FUELS & FEEDSTOCKS/MJ
Totals may not agree because of rounding

	Fuel production	Fuel use	Transport fuels	Feedstock	Total
Coal (use)	46 91	30 06	0 11	<0 01	77 08
Oil (use)	53 67	666 73	5 54	0.01	725 95
Gas (use)	48 62	34 98	0 04	<0 01	83 64
Hydro (use)	0 88	0 36	<0 01	-	1 23
Nuclear (use)	35 27	14.39	0 03	-	49 69
Lignite (use)	0 04	0 01	<0 01	-	0 05
Wood (use)	-	-	-	<0 01	<0 01
Sulphur (use)	<0 01	<0 01	<0 01	<0 01	<0 01
Biomass (use)	0.06	0 02	<0 01	<0 01	0 08
Hydrogen (use)	<0.01	<0 01	<0.01	-	<0.01
Recovered energy (use)	<0 01	<0 01	<0 01	-	<0 01
Unspecified (use)	0.03	0.01	<0 01	-	0 05
Peat (use)	0.01	<0 01	<0 01	-	0 01
Geothermal (use)	<0.01	<0.01	<0 01	-	<0 01
Solar (use)	<0.01	<0 01	<0 01	-	<0 01
Wave/tidal (use)	<0.01	<0.01	<0 01	-	<0 01
Totals	185 48	746.57	5 72	0 01	937 79

FUELS & FEEDSTOCKS (in mg)	
Crude oil	16,132,300
Gas/condensate	1,545,561
Coal.	2,752,493
Metallurgical coal...	1,849
Lignite ..	3,426
Peat .	1,173
Wood (50% water) .	-

OTHER RAW MATERIALS INPUTS/mg

Fe	4,590	air	313	ferromanganese	4
N2	351	barytes	3	gravel	17
O2	81	bauxite	33	limestone (CaCO3)	960
Pb	35	bentonite	3	olivine	43
S (elemental)	18	biomass (including water)	9,520	sand (SiO2)	192,000
Zn	1	dolomite	56	sodium chloride (NaCl)	81

Printout date 13/11/2003
Printout time 13.44 49

continued .. .

Code 6255 ALUMINIUM 4TH SCENARIO (SECONDARY)
Gross data per kg

continued .

AIR EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
Dust	34,223	47,594	271	-209,973	-	-127,885
CO	6,275	465,337	3,163	99	-	474,874
CO2	13,367,883	50,032,865	350,359	4,265	-9,809	63,745,563
SOX	143,193	126,522	1,523	<1	-	271,238
NOX	64,428	590,573	3,952	<1	-	658,953
N2O	<1	<1	-	-	-	<1
Hydrocarbons	24,990	152,928	1,093	<1	-	179,012
Methane	51,170	18,589	-	<1	-	69,759
H2S	<1	-	-	<1	-	<1
HCl	1,280	232	-	<1	-	1,513
Cl2	-	-	-	<1	-	<1
HF	80	9	-	<1	-	89
Lead(Pb)	-	<1	-	<1	-	<1
Metals	8	<1	-	<1	-	8
F2	-	-	-	<1	-	<1
Mercaptans	-	<1	-	<1	-	<1
Organo-Cl	-	-	-	<1	-	<1
Aromatic-HC	-	-	-	9	-	9
Polycyclic-HC	-	-	-	<1	-	<1
Other organics	-	-	-	<1	-	<1
CFC/HCFC	-	-	-	<1	-	<1
Aldehydes (CHO)	-	-	-	<1	-	<1
HCN	-	-	-	<1	-	<1
H2SO4	-	-	-	<1	-	<1
Hydrogen (H2)	<1	-	-	<1	-	<1
Mercury (Hg)	-	-	-	<1	-	<1
Ammonia (NH3)	-	-	-	<1	-	<1
CS2	-	-	-	<1	-	<1
DCE	-	-	-	<1	-	<1
VCM	-	-	-	<1	-	<1
VOC	-	-	-	<1	-	<1
Cu (process)	-	-	-	<1	-	<1
Cd (process)	-	-	-	<1	-	<1
Zn (process)	-	-	-	<1	-	<1
Sb (process)	-	-	-	<1	-	<1

CO2 EQUIVALENTS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equivalent	16,245,928	52,004,517	356,685	4,469	-9,809	68,601,791
100 year equivalent	14,454,993	51,353,905	356,685	4,466	-9,809	66,160,241
500 year equivalent	13,713,034	51,084,366	356,685	4,464	-9,809	65,148,742

SOLID WASTE/mg	Fuel prod'n	Fuel use	Transport	Process	Total
Mineral	516,936	-	-	25,012	541,948
Mixed industrial	72,378	-	-	141	72,520
Slags/ash	130,122	34,799	-	1,392	166,313
Inert chemical	<1	-	-	5	5
Regulated chemical	<1	-	-	<1	<1
Unspecified	<1	-	-	<1	<1
Construction	-	-	-	<1	<1
Metals	-	-	-	<1	<1
To incinerator	-	-	-	2	2
Plastic containers	-	-	-	<1	<1
Paper & board	-	-	-	<1	<1
Plastics	-	-	-	<1	<1
Putrescibles	-	-	-	1	1
Wood waste	-	-	-	<1	<1
Wooden pallets	-	-	-	<1	<1
To recycling	-	-	-	<1	<1
Waste returned to mine	-	-	-	116	116
Tailings	-	-	-	122	122

Printout date 13/11/2003
Printout time 13.44 49

continued

Code. 6255 ALUMINIUM 4TH SCENARIO (SECONDARY)
Gross data per kg
continued .

WATER EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Total
COD	838	-	-	3	842
BOD	724	-	-	<1	724
Acid (H+)	53	-	-	<1	53
Dissolved solids	<1	-	-	<1	<1
Hydrocarbons	724	<1	-	<1	724
NH4	47	-	-	<1	47
Suspended solids	806	-	-	374	1,180
Phenol	724	-	-	<1	724
Al+++	-	-	-	<1	<1
Ca++	-	-	-	<1	<1
Cu++/Cu+++	-	-	-	<1	<1
Fe++/Fe+++	-	-	-	<1	<1
Hg	-	-	-	<1	<1
Pb	-	-	-	<1	<1
Mg++	-	-	-	<1	<1
Na+	-	-	-	16	16
K+	-	-	-	<1	<1
Ni++	-	-	-	<1	<1
Zn++	-	-	-	<1	<1
Other metals	13	-	-	<1	13
NO3-	-	-	-	<1	<1
Other nitrogen	12	-	-	<1	12
BrO3-	-	-	-	<1	<1
CrO3--	-	-	-	<1	<1
Cl-	-	-	-	2	2
ClO3-	-	-	-	<1	<1
CN-	-	-	-	<1	<1
F-	-	-	-	<1	<1
SO4--	-	-	-	<1	<1
CO3--	-	-	-	<1	<1
Phosphate as P2O5	-	-	-	<1	<1
AOX	-	-	-	<1	<1
TOC	-	-	-	<1	<1
Arsenic	-	-	-	<1	<1
DCE	-	-	-	<1	<1
VCM	-	-	-	<1	<1
Detergent/oil	-	-	-	<1	<1
Dissolved Cl2	-	-	-	<1	<1
Organo-chlorine	-	-	-	<1	<1
Dissolved organics	-	-	-	<1	<1
Other organics	-	-	-	<1	<1
Sulphur/sulphide	-	-	-	<1	<1
Cd++	-	-	-	<1	<1
Mn++	-	-	-	<1	<1

WATER USE (in mg)

Source	Use in Process	Use in Cooling	Totals
Public supply	28,730,836	-	28,730,836
River/canal	104	176	280
Sea	223	20,852	21,075
Unspecified	6,075,078	2,147	6,077,225
Well	21	3	24
Totals	34,806,262	23,178	34,829,441

Total cooling water reported in recirculating systems = 0

Printout date 13/11/2003
Printout time 13 44 49

Appendix VI

The LCI results of the base case scenario for the cast iron suspension arm are illustrated in the following pages. The results are presented in printouts from the LCA software tool Boustead 4.4 Model.

Code 6065 CAST IRON SUSPENSION ARM
Gross data per kg

GROSS ENERGY/MJ

Totals may not agree because of rounding

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Elec	43 66	17 95	0 18	0 00	61 78
Oil	96 05	961 69	7 73	0 03	1065 50
Other	4 76	70 77	0 65	5 91	82 10
Total	144 47	1050 41	8 56	5 94	1209.38

PRIMARY FUELS & FEEDSTOCKS/MJ

Totals may not agree because of rounding

	Fuel production	Fuel use	Transport fuels	Feedstock	Total
Coal (use)	19 47	64 02	0 17	5 91	89 57
Oil (use)	71 54	962 62	8 29	0 02	1,042 47
Gas (use)	38.96	18.14	0 06	0 01	57 17
Hydro (use)	0.36	0.14	<0 01	-	0 50
Nuclear (use)	14 06	5 48	0 05	-	19 59
Lignite (use)	0 03	0 01	<0 01	-	0 03
Wood (use)	-	-	-	<0 01	<0 01
Sulphur (use)	<0 01	<0 01	<0 01	<0.01	<0 01
Biomass (use)	0 03	0 01	<0.01	<0 01	0 04
Hydrogen (use)	<0 01	<0 01	<0 01	-	<0 01
Recovered energy (use)	<0 01	<0 01	<0.01	-	<0 01
Unspecified (use)	0 01	0 01	<0.01	-	0 02
Peat (use)	<0 01	<0 01	<0.01	-	<0 01
Geothermal (use)	<0 01	<0 01	<0 01	-	<0 01
Solar (use)	<0 01	<0 01	<0 01	-	<0.01
Wave/tidal (use)	<0 01	<0 01	<0 01	-	<0.01
Totals	144 47	1,050 41	8.56	5 94	1,209 38

FUELS & FEEDSTOCKS (in mg)

Crude oil	23,165,877
Gas/condensate	1,056,381
Coal	3,198,581
Metallurgical coal	1,422,242
Lignite	2,164
Peat	462
Wood (50% water)	-

OTHER RAW MATERIALS INPUTS/mg

Fe	4,951,074	barytes	4	gravel	20,018
N2	527	bauxite	668	limestone (CaCO3)	1,129,348
O2	90,429	bentonite	4,027	olivine	50,901
Pb	53	biomass (including water)	3,982	sand (SiO2)	2,128,000
S (elemental)	32	dolomite	43,598	sodium chloride (NaCl)	128
Zn	2	ferromanganese	6		
air	542	fluorspar	12		

Printout date 13/11/2003
Printout time 13 45 06

continued

Code 6065 CAST IRON SUSPENSION ARM
Gross data per kg

continued

AIR EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
Dust	18,016	67,904	405	4,545	-	90,869
CO	3,520	665,297	4,703	112,305	-	785,825
CO2	10,739,763	72,780,318	529,239	99,805	-4,077	84,145,049
SOX	113,265	197,318	2,431	<1	-	313,014
NOX	39,624	831,494	5,913	518	-	877,548
N2O	<1	<1	-	-	-	<1
Hydrocarbons	31,789	219,155	1,637	420	-	253,002
Methane	35,549	16,792	-	<1	-	52,341
H2S	<1	-	-	181	-	182
HCl	522	407	-	141	-	1,070
Cl2	-	-	-	<1	-	<1
HF	33	15	-	<1	-	48
Lead(Pb)	-	<1	-	2	-	2
Metals	3	5	-	<1	-	8
F2	-	-	-	<1	-	<1
Mercaptans	-	<1	-	<1	-	<1
Organo-Cl	-	-	-	<1	-	<1
Aromatic-HC	-	-	-	14	-	14
Polycyclic-HC	-	-	-	<1	-	<1
Other organics	-	-	-	<1	-	<1
CFC/HCFC	-	-	-	<1	-	<1
Aldehydes (CHO)	-	-	-	<1	-	<1
HCN	-	-	-	<1	-	<1
H2SO4	-	-	-	<1	-	<1
Hydrogen (H2)	<1	-	-	<1	-	<1
Mercury (Hg)	-	-	-	<1	-	<1
Ammonia (NH3)	-	-	-	<1	-	<1
CS2	-	-	-	<1	-	<1
DCE	-	-	-	<1	-	<1
VCM	-	-	-	<1	-	<1
VOC	-	-	-	<1	-	<1
Cu (process)	-	-	-	<1	-	<1
Cd (process)	-	-	-	<1	-	<1
Zn (process)	-	-	-	<1	-	<1
Sb (process)	-	-	-	<1	-	<1

CO2 EQUIVALENTS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equivalent	12,737,522	75,051,264	538,644	324,424	-4,077	88,647,778
100 year equivalent	11,493,323	74,463,545	538,644	324,419	-4,077	86,815,854
500 year equivalent	10,977,869	74,220,061	538,644	324,417	-4,077	86,056,914

SOLID WASTE/mg	Fuel prod'n	Fuel use	Transport	Process	Total
Mineral	600,842	-	-	4,497,583	5,098,425
Mixed industrial	103,935	-	-	43,597	147,532
Slags/ash	53,002	44,512	-	24,863	122,377
Inert chemical	<1	-	-	8	8
Regulated chemical	<1	-	-	<1	<1
Unspecified	<1	-	-	<1	<1
Construction	-	-	-	<1	<1
Metals	-	-	-	<1	<1
To incinerator	-	-	-	3	3
Plastic containers	-	-	-	<1	<1
Paper & board	-	-	-	<1	<1
Plastics	-	-	-	<1	<1
Putrescibles	-	-	-	2	2
Wood waste	-	-	-	<1	<1
Wooden pallets	-	-	-	<1	<1
To recycling	-	-	-	<1	<1
Waste returned to mine	-	-	-	174	174
Tailings	-	-	-	183	183

Printout date 13/11/2003
Printout time 13 45 06

continued ... .

Code 6065 CAST IRON SUSPENSION ARM
Gross data per kg
continued

WATER EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Total
COD	1,165	-	-	363	1,528
BOD	1,039	-	-	<1	1,039
Acid (H+)	17	-	-	97	115
Dissolved solids	<1	-	-	<1	<1
Hydrocarbons	1,039	<1	-	<1	1,040
NH4	15	-	-	159	175
Suspended solids	899	-	-	427,584	428,482
Phenol	1,039	-	-	<1	1,039
Al+++	-	-	-	<1	<1
Ca++	-	-	-	<1	<1
Cu++/Cu+++	-	-	-	<1	<1
Fe++/Fe+++	-	-	-	17	17
Hg	-	-	-	<1	<1
Pb	-	-	-	<1	<1
Mg++	-	-	-	<1	<1
Na+	-	-	-	37	37
K+	-	-	-	<1	<1
Ni++	-	-	-	<1	<1
Zn++	-	-	-	<1	<1
Other metals	4	-	-	27	31
NO3-	-	-	-	<1	<1
Other nitrogen	4	-	-	58	62
BrO3-	-	-	-	<1	<1
CrO3--	-	-	-	<1	<1
Cl-	-	-	-	3	3
ClO3-	-	-	-	<1	<1
CN-	-	-	-	<1	<1
F-	-	-	-	<1	<1
SO4--	-	-	-	1	1
CO3--	-	-	-	<1	<1
Phosphate as P2O5	-	-	-	<1	<1
AOX	-	-	-	<1	<1
TOC	-	-	-	<1	<1
Arsenic	-	-	-	<1	<1
DCE	-	-	-	<1	<1
VCM	-	-	-	<1	<1
Detergent/oil	-	-	-	<1	<1
Dissolved Cl2	-	-	-	<1	<1
Organo-chlorine	-	-	-	<1	<1
Dissolved organics	-	-	-	<1	<1
Other organics	-	-	-	<1	<1
Sulphur/sulphide	-	-	-	<1	<1
Cd++	-	-	-	<1	<1
Mn++	-	-	-	<1	<1

WATER USE (in mg)

Source	Use in Process	Use in Cooling	Totals
Public supply	111,767,983	-	111,767,983
River/canal	156	748	904
Sea	346	31,497	31,844
Unspecified	7,062,131	3,570	7,065,701
Well	32	12	44
Totals	118,830,648	35,827	118,866,475

Total cooling water reported in recirculating systems = 1

Printout date 13/11/2003
Printout time 13 45 06

Appendix VII

The LCI results of the 1st Scenario for the cast iron suspension arm are illustrated in the following pages. The results are presented in printouts from the LCA software tool Boustead 4.4 Model.

Code 6098 CAST IRON 1ST SCENARIO (75/25)
Gross data per kg

GROSS ENERGY/MJ
Totals may not agree because of rounding

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Elec	42 24	17 37	0 17	0 00	59 79
Oil	95.72	958 49	7.63	0 02	1061 87
Other	4 04	57 14	0 50	4 44	66 12
Total	142 00	1033 00	8 31	4.46	1187.78

PRIMARY FUELS & FEEDSTOCKS/MJ
Totals may not agree because of rounding

	Fuel production	Fuel use	Transport fuels	Feedstock	Total
Coal (use)	18 54	50 50	0 16	4 43	73 63
Oil (use)	71 19	959 39	8 05	0 02	1,038 64
Gas (use)	38 36	17 66	0 06	0 01	56 09
Hydro (use)	0 34	0.13	<0 01	-	0 48
Nuclear (use)	13 51	5.30	0 05	-	18 85
Lignite (use)	0 02	0 01	<0 01	-	0 03
Wood (use)	-	-	-	<0 01	<0 01
Sulphur (use)	<0 01	<0 01	<0 01	<0 01	<0 01
Biomass (use)	0 02	0 01	<0 01	<0 01	0 03
Hydrogen (use)	<0 01	<0 01	<0 01	-	<0 01
Recovered energy (use)	<0 01	<0 01	<0 01	-	<0 01
Unspecified (use)	0 01	<0 01	<0 01	-	0 02
Peat (use)	<0 01	<0 01	<0.01	-	<0 01
Geothermal (use)	<0.01	<0 01	<0.01	-	<0 01
Solar (use)	<0 01	<0 01	<0 01	-	<0 01
Wave/tidal (use)	<0 01	<0 01	<0.01	-	<0 01
Totals	142 00	1,033 00	8.31	4 46	1,187 78

FUELS & FEEDSTOCKS (in mg)

Crude oil . . .	23,080,811
Gas/condensate . .	1,036,463
Coal.	2,629,590
Metallurgical coal	1,067,268
Lignite	1,912
Peat.	445
Wood (50% water). . .	-

OTHER RAW MATERIALS INPUTS/mg

Fe	3,714,760	barytes	4	gravel	15,019
N2	507	bauxite	507	limestone (CaCO3)	847,315
O2	67,847	bentonite	3,021	olivine	38,190
Pb	51	biomass (including water)	3,784	sand (SiO2)	2,128,000
S (elemental)	30	dolomite	32,716	sodium chloride (NaCl)	122
Zn	2	ferromanganese	6		
air	505	fluorspar	9		

Printout date 13/11/2003
Printout time 13 45 19

continued

Code 6098 CAST IRON 1ST SCENARIO (75/25)
Gross data per kg

continued

AIR EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
Dust	16,706	66,214	393	3,415	-	86,728
CO	3,437	664,994	4,568	84,260	-	757,259
CO2	10,566,491	71,747,465	513,086	76,050	-3,879	82,899,213
SOX	111,623	191,354	2,341	<1	-	305,319
NOX	38,721	829,472	5,739	388	-	874,321
N2O	<1	<1	-	-	-	<1
Hydrocarbons	31,610	218,938	1,589	315	-	252,452
Methane	34,883	16,605	-	<1	-	51,489
H2S	<1	-	-	136	-	136
HCl	499	324	-	106	-	929
Cl2	-	-	-	<1	-	<1
HF	31	12	-	<1	-	43
Lead(Pb)	-	<1	-	1	-	1
Metals	3	4	-	<1	-	7
F2	-	-	-	<1	-	<1
Mercaptans	-	<1	-	<1	-	<1
Organo-Cl	-	-	-	<1	-	<1
Aromatic-HC	-	-	-	13	-	13
Polycyclic-HC	-	-	-	<1	-	<1
Other organics	-	-	-	<1	-	<1
CFC/HCFC	-	-	-	<1	-	<1
Aldehydes (CHO)	-	-	-	<1	-	<1
HCN	-	-	-	<1	-	<1
H2SO4	-	-	-	<1	-	<1
Hydrogen (H2)	<1	-	-	<1	-	<1
Mercury (Hg)	-	-	-	<1	-	<1
Ammonia (NH3)	-	-	-	<1	-	<1
CS2	-	-	-	<1	-	<1
DCE	-	-	-	<1	-	<1
VCM	-	-	-	<1	-	<1
VOC	-	-	-	<1	-	<1
Cu (process)	-	-	-	<1	-	<1
Cd (process)	-	-	-	<1	-	<1
Zn (process)	-	-	-	<1	-	<1
Sb (process)	-	-	-	<1	-	<1

CO2 EQUIVALENTS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equivalent	12,526,826	74,007,347	522,222	244,579	-3,879	87,297,094
100 year equivalent	11,305,912	73,426,163	522,222	244,574	-3,879	85,494,992
500 year equivalent	10,800,105	73,185,387	522,222	244,572	-3,879	84,748,407

SOLID WASTE/mg	Fuel prod'n	Fuel use	Transport	Process	Total
Mineral	493,950	-	-	3,433,405	3,927,355
Mixed industrial	103,553	-	-	32,742	136,296
Slags/ash	50,647	36,273	-	19,088	106,008
Inert chemical	<1	-	-	7	7
Regulated chemical	<1	-	-	<1	<1
Unspecified	<1	-	-	<1	<1
Construction	-	-	-	<1	<1
Metals	-	-	-	<1	<1
To incinerator	-	-	-	2	2
Plastic containers	-	-	-	<1	<1
Paper & board	-	-	-	<1	<1
Plastics	-	-	-	<1	<1
Putrescibles	-	-	-	1	1
Wood waste	-	-	-	<1	<1
Wooden pallets	-	-	-	<1	<1
To recycling	-	-	-	<1	<1
Waste returned to mine	-	-	-	167	167
Tailings	-	-	-	176	176

Printout date 13/11/2003
Printout time 13 45 19

continued .

Code 6098 CAST IRON 1ST SCENARIO (75/25)
Gross data per kg
continued

WATER EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Total
COD	1,161	-	-	273	1,434
BOD	1,036	-	-	<1	1,036
Acid (H+)	17	-	-	73	90
Dissolved solids	<1	-	-	<1	<1
Hydrocarbons	1,036	<1	-	<1	1,036
NH4	15	-	-	120	135
Suspended solids	741	-	-	320,820	321,562
Phenol	1,036	-	-	<1	1,036
Al+++	-	-	-	<1	<1
Ca++	-	-	-	<1	<1
Cu++/Cu+++	-	-	-	<1	<1
Fe++/Fe+++	-	-	-	13	13
Hg	-	-	-	<1	<1
Pb	-	-	-	<1	<1
Mg++	-	-	-	<1	<1
Na+	-	-	-	33	33
K+	-	-	-	<1	<1
Ni++	-	-	-	<1	<1
Zn++	-	-	-	<1	<1
Other metals	4	-	-	20	25
NO3-	-	-	-	<1	<1
Other nitrogen	4	-	-	44	47
BrO3-	-	-	-	<1	<1
CrO3--	-	-	-	<1	<1
Cl-	-	-	-	3	3
ClO3-	-	-	-	<1	<1
CN-	-	-	-	<1	<1
F-	-	-	-	<1	<1
SO4--	-	-	-	<1	<1
CO3--	-	-	-	<1	<1
Phosphate as P2O5	-	-	-	<1	<1
AOX	-	-	-	<1	<1
TOC	-	-	-	<1	<1
Arsenic	-	-	-	<1	<1
DCE	-	-	-	<1	<1
VCM	-	-	-	<1	<1
Detergent/oil	-	-	-	<1	<1
Dissolved Cl2	-	-	-	<1	<1
Organo-chlorine	-	-	-	<1	<1
Dissolved organics	-	-	-	<1	<1
Other organics	-	-	-	<1	<1
Sulphur/sulphide	-	-	-	<1	<1
Cd++	-	-	-	<1	<1
Mn++	-	-	-	<1	<1

WATER USE (in mg)

Source	Use in Process	Use in Cooling	Totals
Public supply	95,780,204	-	95,780,204
River/canal	150	617	767
Sea	331	30,252	30,583
Unspecified	5,805,755	3,360	5,809,115
Well	31	10	41
Totals	101,586,470	34,239	101,620,709

Total cooling water reported in recirculating systems = 1

Printout date 13/11/2003
Printout time: 13 45 19

Appendix VIII

The LCI results of the 2^{nd} Scenario for the cast iron suspension arm are presented in the following pages. The results are presented in printouts from the LCA software tool Boustead 4.4 Model.

```
Code  6079 CAST IRON 2ND SCENARIO (50/50)
Gross data per kg


GROSS ENERGY/MJ
Totals may not agree because of rounding

 Fuel       Fuel        Energy      Transport  Feedstock   Total
 type       prod'n &    content     energy     energy      energy
            delivery    of fuel

 Elec         40 83       16 79       0 16       0 00        57 79
 Oil          95 40      955 29       7 54       0 02      1058.25
 Other         3 31       43 52       0 35       2 96        50.14

 Total       139 54     1015 60       8 06       2 98      1166 17


PRIMARY FUELS & FEEDSTOCKS/MJ
Totals may not agree because of rounding

                                Fuel              Fuel          Transport           Feedstock             Total
                          production               use              fuels

Coal (use)                     17 60             36.99               0 16                2 96             57 70
Oil (use)                      70 84            956.16               7 80                0 02          1,034 81
Gas (use)                      37 76             17 18               0 06                0 01             55.01
Hydro (use)                     0 33              0 13              <0 01                   -              0 46
Nuclear (use)                  12 95              5 12               0 05                   -             18 11
Lignite (use)                   0 02              0 01              <0 01                   -              0 03
Wood (use)                         -                 -                  -               <0.01             <0 01
Sulphur (use)                  <0 01             <0 01              <0 01               <0 01             <0 01
Biomass (use)                   0 02              0 01              <0 01               <0 01              0 03
Hydrogen (use)                 <0 01             <0 01              <0 01                   -             <0 01
Recovered energy (use)         <0 01             <0 01              <0 01                   -             <0.01
Unspecified (use)               0 01             <0 01              <0 01                   -              0 02
Peat (use)                     <0 01             <0 01              <0 01                   -             <0 01
Geothermal (use)               <0 01             <0 01              <0 01                   -             <0 01
Solar (use)                    <0 01             <0 01              <0 01                   -             <0 01
Wave/tidal (use)               <0 01             <0 01              <0 01                   -             <0 01

Totals                        139 54          1,015 60               8 06                2 98          1,166 17


FUELS & FEEDSTOCKS (in mg)

Crude oil                 22,995,745
Gas/condensate             1,016,545
Coal. .... .       . .     2,060,598
Metallurgical coal           712,293
Lignite                        1,659
Peat                             427
Wood (50% water)                   -


OTHER RAW MATERIALS INPUTS/mg

Fe                             2,478,446 barytes                                4 gravel                        10,020
N2                                   487 bauxite                              346 limestone (CaCO3)            565,282
O2                                45,266 bentonite                          2,016 olivine                       25,478
Pb                                    49 biomass (including water)          3,586 sand (SiO2)                2,128,000
S (elemental)                         28 dolomite                          21,834 sodium chloride (NaCl)           115
Zn                                     2 ferromanganese                         6
air                                  468 fluorspar                              6

Printout date  13/11/2003
Printout time  13 45 32
                                                                                  continued    ..
```

Code 6079 CAST IRON 2ND SCENARIO (50/50)
Gross data per kg

continued .

AIR EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
Dust	15,397	64,524	381	2,285	-	82,586
CO	3,353	664,691	4,433	56,215	-	728,692
CO2	10,393,220	70,714,611	496,933	52,295	-3,681	81,653,378
SOX	109,982	185,389	2,252	<1	-	297,623
NOX	37,818	827,451	5,565	259	-	871,093
N2O	<1	<1	-	-	-	<1
Hydrocarbons	31,430	218,720	1,541	210	-	251,902
Methane	34,218	16,419	-	<1	-	50,637
H2S	<1	-	-	91	-	91
HCl	476	242	-	71	-	788
Cl2	-	-	-	<1	-	<1
HF	30	9	-	<1	-	39
Lead(Pb)	-	<1	-	<1	-	<1
Metals	3	3	-	<1	-	6
F2	-	-	-	<1	-	<1
Mercaptans	-	<1	-	<1	-	<1
Organo-Cl	-	-	-	<1	-	<1
Aromatic-HC	-	-	-	13	-	13
Polycyclic-HC	-	-	-	<1	-	<1
Other organics	-	-	-	<1	-	<1
CFC/HCFC	-	-	-	<1	-	<1
Aldehydes (CHO)	-	-	-	<1	-	<1
HCN	-	-	-	<1	-	<1
H2SO4	-	-	-	<1	-	<1
Hydrogen (H2)	<1	-	-	<1	-	<1
Mercury (Hg)	-	-	-	<1	-	<1
Ammonia (NH3)	-	-	-	<1	-	<1
CS2	-	-	-	<1	-	<1
DCE	-	-	-	<1	-	<1
VCM	-	-	-	<1	-	<1
VOC	-	-	-	<1	-	<1
Cu (process)	-	-	-	<1	-	<1
Cd (process)	-	-	-	<1	-	<1
Zn (process)	-	-	-	<1	-	<1
Sb (process)	-	-	-	<1	-	<1

CO2 EQUIVALENTS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equivalent	12,316,129	72,963,429	505,800	164,734	-3,681	85,946,411
100 year equivalent	11,118,502	72,388,782	505,800	164,729	-3,681	84,174,131
500 year equivalent	10,622,342	72,150,713	505,800	164,727	-3,681	83,439,900

SOLID WASTE/mg	Fuel prod'n	Fuel use	Transport	Process	Total
Mineral	387,058	-	-	2,369,227	2,756,285
Mixed industrial	103,172	-	-	21,888	125,060
Slags/ash	48,292	28,035	-	13,313	89,639
Inert chemical	<1	-	-	7	7
Regulated chemical	<1	-	-	<1	<1
Unspecified	<1	-	-	<1	<1
Construction	-	-	-	<1	<1
Metals	-	-	-	<1	<1
To incinerator	-	-	-	2	2
Plastic containers	-	-	-	<1	<1
Paper & board	-	-	-	<1	<1
Plastics	-	-	-	<1	<1
Putrescibles	-	-	-	1	1
Wood waste	-	-	-	<1	<1
Wooden pallets	-	-	-	<1	<1
To recycling	-	-	-	<1	<1
Waste returned to mine	-	-	-	161	161
Tailings	-	-	-	169	169

Printout date 13/11/2003
Printout time 13.45 32

continued .....

Code 6079 CAST IRON 2ND SCENARIO (50/50)
Gross data per kg
continued

WATER EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Total
COD	1,157	-	-	184	1,340
BOD	1,032	-	-	<1	1,032
Acid (H+)	17	-	-	49	66
Dissolved solids	<1	-	-	<1	<1
Hydrocarbons	1,032	<1	-	<1	1,032
NH4	15	-	-	80	95
Suspended solids	584	-	-	214,057	214,641
Phenol	1,032	-	-	<1	1,032
Al+++	-	-	-	<1	<1
Ca++	-	-	-	<1	<1
Cu++/Cu+++	-	-	-	<1	<1
Fe++/Fe+++	-	-	-	8	8
Hg	-	-	-	<1	<1
Pb	-	-	-	<1	<1
Mg++	-	-	-	<1	<1
Na+	-	-	-	29	29
K+	-	-	-	<1	<1
Ni++	-	-	-	<1	<1
Zn++	-	-	-	<1	<1
Other metals	4	-	-	14	18
NO3-	-	-	-	<1	<1
Other nitrogen	4	-	-	29	33
BrO3-	-	-	-	<1	<1
CrO3--	-	-	-	<1	<1
Cl-	-	-	-	3	3
ClO3-	-	-	-	<1	<1
CN-	-	-	-	<1	<1
F-	-	-	-	<1	<1
SO4--	-	-	-	<1	<1
CO3--	-	-	-	<1	<1
Phosphate as P2O5	-	-	-	<1	<1
AOX	-	-	-	<1	<1
TOC	-	-	-	<1	<1
Arsenic	-	-	-	<1	<1
DCE	-	-	-	<1	<1
VCM	-	-	-	<1	<1
Detergent/oil	-	-	-	<1	<1
Dissolved Cl2	-	-	-	<1	<1
Organo-chlorine	-	-	-	<1	<1
Dissolved organics	-	-	-	<1	<1
Other organics	-	-	-	<1	<1
Sulphur/sulphide	-	-	-	<1	<1
Cd++	-	-	-	<1	<1
Mn++	-	-	-	<1	<1

WATER USE (in mg)

Source	Use in Process	Use in Cooling	Totals
Public supply	79,792,425	-	79,792,425
River/canal	144	486	630
Sea	315	29,007	29,322
Unspecified	4,549,379	3,150	4,552,529
Well	30	8	38
Totals	84,342,292	32,651	84,374,944

Total cooling water reported in recirculating systems = 1

Printout date 13/11/2003
Printout time 13 45 32

Appendix IX

The LCI results of the 3rd Scenario for the cast iron suspension arm are illustrated in the following pages. The results are presented in printouts from the LCA software tool Boustead 4.4 Model.

Code 6121 CAST IRON 3RD SCENARIO (25/75)
Gross data per kg

GROSS ENERGY/MJ
Totals may not agree because of rounding

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Elec	39 42	16 21	0 16	0 00	55.79
Oil	95 07	952 09	7 44	0 02	1054 62
Other	2 59	29 89	0 20	1 48	34 16
Total	137 07	998 19	7 80	1 50	1144 57

PRIMARY FUELS & FEEDSTOCKS/MJ
Totals may not agree because of rounding

	Fuel production	Fuel use	Transport fuels	Feedstock	Total
Coal (use)	16 67	23 47	0 15	1.48	41 77
Oil (use)	70 49	952 92	7.56	0 01	1,030 98
Gas (use)	37 16	16 71	0.05	0 01	53 93
Hydro (use)	0 31	0 12	<0.01	-	0 44
Nuclear (use)	12 39	4 94	0 04	-	17 38
Lignite (use)	0 02	0 01	<0 01	-	0 02
Wood (use)	-	-	-	<0.01	<0 01
Sulphur (use)	<0 01	<0 01	<0 01	<0 01	<0 01
Biomass (use)	0.02	0 01	<0 01	<0 01	0 03
Hydrogen (use)	<0 01	<0 01	<0.01	-	<0 01
Recovered energy (use)	<0 01	<0 01	<0 01	-	<0 01
Unspecified (use)	0 01	<0 01	<0 01	-	0 02
Peat (use)	<0 01	<0 01	<0 01	-	<0 01
Geothermal (use)	<0 01	<0 01	<0.01	-	<0 01
Solar (use)	<0 01	<0 01	<0 01	-	<0 01
Wave/tidal (use)	<0 01	<0 01	<0 01	-	<0 01
Totals	137 07	998 19	7 80	1 50	1,144 57

FUELS & FEEDSTOCKS (in mg)	
Crude oil	22,910,679
Gas/condensate	996,627
Coal	1,491,606
Metallurgical coal .	357,319
Lignite ..	1,407
Peat . .	410
Wood (50% water) . .	-

OTHER RAW MATERIALS INPUTS/mg

Fe	1,242,132	barytes	4	gravel	5,021
N2	467	bauxite	185	limestone (CaCO3)	283,249
O2	22,684	bentonite	1,010	olivine	12,766
Pb	47	biomass (including water)	3,388	sand (SiO2)	2,128,000
S (elemental)	25	dolomite	10,953	sodium chloride (NaCl)	109
Zn	2	ferromanganese	6		
air	431	fluorspar	3		

Printout date 13/11/2003
Printout time 13 45 47

continued ....

Code 6121 CAST IRON 3RD SCENARIO (25/75)
Gross data per kg

continued

AIR EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
Dust	14,087	62,833	369	1,156	-	78,445
CO	3,269	664,387	4,299	28,171	-	700,126
CO2	10,219,949	69,681,758	480,780	28,540	-3,484	80,407,543
SOX	108,340	179,424	2,163	<1	-	289,928
NOX	36,915	825,429	5,392	130	-	867,866
N2O	<1	<1	-	-	-	<1
Hydrocarbons	31,250	218,503	1,493	106	-	251,352
Methane	33,553	16,232	-	<1	-	49,785
H2S	<1	-	-	45	-	46
HCl	452	160	-	35	-	647
Cl2	-	-	-	<1	-	<1
HF	28	6	-	<1	-	34
Lead(Pb)	-	<1	-	<1	-	<1
Metals	3	1	-	<1	-	4
F2	-	-	-	<1	-	<1
Mercaptans	-	<1	-	<1	-	<1
Organo-Cl	-	-	-	<1	-	<1
Aromatic-HC	-	-	-	12	-	12
Polycyclic-HC	-	-	-	<1	-	<1
Other organics	-	-	-	<1	-	<1
CFC/HCFC	-	-	-	<1	-	<1
Aldehydes (CHO)	-	-	-	<1	-	<1
HCN	-	-	-	<1	-	<1
H2SO4	-	-	-	<1	-	<1
Hydrogen (H2)	<1	-	-	<1	-	<1
Mercury (Hg)	-	-	-	<1	-	<1
Ammonia (NH3)	-	-	-	<1	-	<1
CS2	-	-	-	<1	-	<1
DCE	-	-	-	<1	-	<1
VCM	-	-	-	<1	-	<1
VOC	-	-	-	<1	-	<1
Cu (process)	-	-	-	<1	-	<1
Cd (process)	-	-	-	<1	-	<1
Zn (process)	-	-	-	<1	-	<1
Sb (process)	-	-	-	<1	-	<1

CO2 EQUIVALENTS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equivalent	12,105,433	71,919,512	489,377	84,888	-3,484	84,595,727
100 year equivalent	10,931,091	71,351,400	489,377	84,884	-3,484	82,853,269
500 year equivalent	10,444,578	71,116,040	489,377	84,882	-3,484	82,131,393

SOLID WASTE/mg	Fuel prod'n	Fuel use	Transport	Process	Total
Mineral	280,166	-	-	1,305,049	1,585,215
Mixed industrial	102,790	-	-	11,033	113,824
Slags/ash	45,936	19,796	-	7,538	73,271
Inert chemical	<1	-	-	6	6
Regulated chemical	<1	-	-	<1	<1
Unspecified	<1	-	-	<1	<1
Construction	-	-	-	<1	<1
Metals	-	-	-	<1	<1
To incinerator	-	-	-	2	2
Plastic containers	-	-	-	<1	<1
Paper & board	-	-	-	<1	<1
Plastics	-	-	-	<1	<1
Putrescibles	-	-	-	1	1
Wood waste	-	-	-	<1	<1
Wooden pallets	-	-	-	<1	<1
To recycling	-	-	-	<1	<1
Waste returned to mine	-	-	-	154	154
Tailings	-	-	-	162	162

Printout date 13/11/2003
Printout time 13 45 47

continued ....

Code 6121 CAST IRON 3RD SCENARIO (25/75)
Gross data per kg
continued .

WATER EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Total
COD	1,153	-	-	94	1,246
BOD	1,028	-	-	<1	1,028
Acid (H+)	17	-	-	24	42
Dissolved solids	<1	-	-	<1	<1
Hydrocarbons	1,028	<1	-	<1	1,028
NH4	15	-	-	40	55
Suspended solids	427	-	-	107,293	107,720
Phenol	1,028	-	-	<1	1,028
Al+++	-	-	-	<1	<1
Ca++	-	-	-	<1	<1
Cu++/Cu+++	-	-	-	<1	<1
Fe++/Fe+++	-	-	-	4	4
Hg	-	-	-	<1	<1
Pb	-	-	-	<1	<1
Mg++	-	-	-	<1	<1
Na+	-	-	-	25	25
K+	-	-	-	<1	<1
Ni++	-	-	-	<1	<1
Zn++	-	-	-	<1	<1
Other metals	4	-	-	7	11
NO3-	-	-	-	<1	<1
Other nitrogen	4	-	-	15	18
BrO3-	-	-	-	<1	<1
CrO3--	-	-	-	<1	<1
Cl-	-	-	-	2	2
ClO3-	-	-	-	<1	<1
CN-	-	-	-	<1	<1
F-	-	-	-	<1	<1
SO4--	-	-	-	<1	<1
CO3--	-	-	-	<1	<1
Phosphate as P2O5	-	-	-	<1	<1
AOX	-	-	-	<1	<1
TOC	-	-	-	<1	<1
Arsenic	-	-	-	<1	<1
DCE	-	-	-	<1	<1
VCM	-	-	-	<1	<1
Detergent/oil	-	-	-	<1	<1
Dissolved Cl2	-	-	-	<1	<1
Organo-chlorine	-	-	-	<1	<1
Dissolved organics	-	-	-	<1	<1
Other organics	-	-	-	<1	<1
Sulphur/sulphide	-	-	-	<1	<1
Cd++	-	-	-	<1	<1
Mn++	-	-	-	<1	<1

WATER USE (in mg)

Source	Use in Process	Use in Cooling	Totals
Public supply	63,804,646	-	63,804,646
River/canal	138	355	493
Sea	299	27,763	28,062
Unspecified	3,293,003	2,940	3,295,943
Well	28	6	34
Totals	67,098,114	31,063	67,129,178

Total cooling water reported in recirculating systems = 1

Printout date 13/11/2003
Printout time 13 45 47

Appendix X

The LCI results of the 4th Scenario for the cast iron suspension arm are presented in the following pages. The results are presented in printouts from the LCA software tool Boustead 4.4 Model.

Code 6141 CAST IRON 4TH SCENARIO (SECONDARY)
Gross data per kg

GROSS ENERGY/MJ
Totals may not agree because of rounding

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Elec	32 36	13 30	0 13	0 00	45.79
Oil	93 44	936 08	6 96	0 01	1036 49
Other	-1 04	-38 23	-0 55	-5.91	-45 72
Total	124 75	911 16	6 54	-5 91	1036 55

PRIMARY FUELS & FEEDSTOCKS/MJ
Totals may not agree because of rounding

	Fuel production	Fuel use	Transport fuels	Feedstock	Total
Coal (use)	11.99	-44 10	0 13	-5 91	-37 90
Oil (use)	68 74	936 77	6 33	<0 01	1,011 84
Gas (use)	34 17	14 32	0 05	0 01	48 54
Hydro (use)	0 23	0 10	<0 01	-	0 32
Nuclear (use)	9 60	4 06	0 04	-	13 70
Lignite (use)	<0 01	<0 01	<0 01	-	<0 01
Wood (use)	-	-	-	<0 01	<0 01
Sulphur (use)	<0 01	<0 01	<0 01	<0 01	<0 01
Biomass (use)	0 01	0.01	<0 01	<0 01	0 02
Hydrogen (use)	<0 01	<0.01	<0 01	-	<0 01
Recovered energy (use)	<0 01	<0 01	<0 01	-	<0 01
Unspecified (use)	0 01	<0 01	<0 01	-	0 01
Peat (use)	<0 01	<0 01	<0 01	-	<0 01
Geothermal (use)	<0 01	<0 01	<0 01	-	<0 01
Solar (use)	<0 01	<0 01	<0 01	-	<0 01
Wave/tidal (use)	<0 01	<0 01	<0 01	-	<0 01
Totals	124 75	911 16	6 54	-5 91	1,036 55

FUELS & FEEDSTOCKS (in mg)

Crude oil .	22,485,349
Gas/condensate	897,037
Coal .. .	-1,353,352
Metallurgical coal.	-1,417,554
Lignite .	146
Peat.	324
Wood (50% water). .	-

OTHER RAW MATERIALS INPUTS/mg

N2	366	air	247	sand (SiO2)	2,128,000
Pb	37	barytes	3	sodium chloride (NaCl)	78
S (elemental)	14	biomass (including water)	2,397		
Zn	1	ferromanganese	4		

Printout date 13/11/2003
Printout time 13 46 04

continued

Code 6141 CAST IRON 4TH SCENARIO (SECONDARY)
Gross data per kg

continued

AIR EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
Dust	7,540	54,381	309	-4,492	-	57,738
CO	2,849	662,871	3,626	-112,054	-	557,292
CO2	9,353,592	64,517,492	400,014	-90,237	-2,495	74,178,366
SOX	100,133	149,601	1,716	<1	-	251,450
NOX	32,401	815,322	4,522	-516	-	851,728
N2O	<1	<1	-	-	-	<1
Hydrocarbons	30,352	217,417	1,252	-418	-	248,603
Methane	30,226	15,298	-	<1	-	45,524
H2S	<1	-	-	-181	-	-181
HCl	336	-252	-	-141	-	-58
Cl2	-	-	-	<1	-	<1
HF	21	-9	-	<1	-	11
Lead(Pb)	-	<1	-	-2	-	-2
Metals	2	-5	-	<1	-	-3
F2	-	-	-	<1	-	<1
Mercaptans	-	<1	-	<1	-	<1
Organo-Cl	-	-	-	<1	-	<1
Aromatic-HC	-	-	-	10	-	10
Polycyclic-HC	-	-	-	<1	-	<1
Other organics	-	-	-	<1	-	<1
CFC/HCFC	-	-	-	<1	-	<1
Aldehydes (CHO)	-	-	-	<1	-	<1
HCN	-	-	-	<1	-	<1
H2SO4	-	-	-	<1	-	<1
Hydrogen (H2)	<1	-	-	<1	-	<1
Mercury (Hg)	-	-	-	<1	-	<1
Ammonia (NH3)	-	-	-	<1	-	<1
CS2	-	-	-	<1	-	<1
DCE	-	-	-	<1	-	<1
VCM	-	-	-	<1	-	<1
VOC	-	-	-	<1	-	<1
Cu (process)	-	-	-	<1	-	<1
Cd (process)	-	-	-	<1	-	<1
Zn (process)	-	-	-	<1	-	<1
Sb (process)	-	-	-	<1	-	<1

CO2 EQUIVALENTS/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equivalent	11,051,950	66,699,925	407,265	-314,338	-2,495	77,842,307
100 year equivalent	9,994,038	66,164,493	407,265	-314,342	-2,495	76,248,960
500 year equivalent	9,555,760	65,942,671	407,265	-314,343	-2,495	75,588,859

SOLID WASTE/mg	Fuel prod'n	Fuel use	Transport	Process	Total
Mineral	-254,292	-	-	-4,015,842	-4,270,135
Mixed industrial	100,882	-	-	-43,239	57,643
Slags/ash	34,160	-21,397	-	-21,336	-8,573
Inert chemical	<1	-	-	5	5
Regulated chemical	<1	-	-	<1	<1
Unspecified	<1	-	-	<1	<1
Construction	-	-	-	<1	<1
Metals	-	-	-	<1	<1
To incinerator	-	-	-	2	2
Plastic containers	-	-	-	<1	<1
Paper & board	-	-	-	<1	<1
Plastics	-	-	-	<1	<1
Putrescibles	-	-	-	1	1
Wood waste	-	-	-	<1	<1
Wooden pallets	-	-	-	<1	<1
To recycling	-	-	-	<1	<1
Waste returned to mine	-	-	-	121	121
Tailings	-	-	-	128	128

Printout date 13/11/2003
Printout time 13 46 04

continued

Code 6141 CAST IRON 4TH SCENARIO (SECONDARY)
Gross data per kg
continued .

WATER EMISSIONS/mg	Fuel prod'n	Fuel use	Transport	Process	Total
COD	1,131	-	-	-355	777
BOD	1,009	-	-	<1	1,009
Acid (H+)	17	-	-	-97	-80
Dissolved solids	<1	-	-	<1	<1
Hydrocarbons	1,009	<1	-	<1	1,009
NH4	15	-	-	-159	-143
Suspended solids	-358	-	-	-426,525	-426,883
Phenol	1,009	-	-	<1	1,009
Al+++	-	-	-	<1	<1
Ca++	-	-	-	<1	<1
Cu++/Cu+++	-	-	-	<1	<1
Fe++/Fe+++	-	-	-	-16	-16
Hg	-	-	-	<1	<1
Pb	-	-	-	<1	<1
Mg++	-	-	-	<1	<1
Na+	-	-	-	4	4
K+	-	-	-	<1	<1
Ni++	-	-	-	<1	<1
Zn++	-	-	-	<1	<1
Other metals	4	-	-	-27	-23
NO3-	-	-	-	<1	<1
Other nitrogen	4	-	-	-58	-54
BrO3-	-	-	-	<1	<1
CrO3--	-	-	-	<1	<1
Cl-	-	-	-	1	1
ClO3-	-	-	-	<1	<1
CN-	-	-	-	<1	<1
F-	-	-	-	<1	<1
SO4--	-	-	-	<1	<1
CO3--	-	-	-	<1	<1
Phosphate as P2O5	-	-	-	<1	<1
AOX	-	-	-	<1	<1
TOC	-	-	-	<1	<1
Arsenic	-	-	-	<1	<1
DCE	-	-	-	<1	<1
VCM	-	-	-	<1	<1
Detergent/oil	-	-	-	<1	<1
Dissolved Cl2	-	-	-	<1	<1
Organo-chlorine	-	-	-	<1	<1
Dissolved organics	-	-	-	<1	<1
Other organics	-	-	-	<1	<1
Sulphur/sulphide	-	-	-	<1	<1
Cd++	-	-	-	<1	<1
Mn++	-	-	-	<1	<1

WATER USE (in mg)

Source	Use in Process	Use in Cooling	Totals
Public supply	-16,134,249	-	-16,134,249
River/canal	109	-300	-191
Sea	221	21,538	21,759
Unspecified	-2,988,877	1,890	-2,986,987
Well	22	-5	18
Totals	-19,122,775	23,124	-19,099,651

Total cooling water reported in recirculating systems = 0

Printout date 13/11/2003
Printout time 13 46 04

Appendix XI

This paper presented at the *"Second International Conference on Design and Manufacture for Sustainable Development"* at the University of Cambridge on September 3-4, 2003

Potential for Vehicle Weight Reduction Using a New Ductile Cast Iron

A J Clegg, T Staikos and C J Backhouse

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, UK

Abstract

This paper reviews steps being taken to reduce the automotive industry's impacts on the environment by reducing vehicle weight. The paper refers to a EU-funded research programme (DILIGHT) to develop a new generation of ductile cast iron for light weight automotive components. A detailed Life Cycle Assessment (LCA) must be conducted to compare the environmental impacts of specific cast automotive components produced in conventional cast iron, aluminium alloy and the proposed DILIGHT alloy. The paper presents the preliminary results for the LCA, which suggest that a vehicle must complete 300,000 km before obtaining the environmental advantage of aluminium's lower density.

1 INTRODUCTION

Growing concern for our environment by stakeholders has led to increasing pressure on the industrial sector to reduce material consumption and minimize harmful releases to air, water and land. The automotive industry, as one of the largest and most complex industrial sectors on a global scale, is exposed to harsh criticism for its environmental pollution. The most serious environmental problem is the enormous consumption of non-renewable energy during the use phase. Motor vehicles burn fossil fuels and produce carbon dioxide (CO_2) emissions, the main greenhouse gas responsible for man-made global climate change.

Reducing the weight of automobiles reduces their fuel consumption and air pollution, especially CO_2 emissions. A 1% vehicle mass reduction yields a 0.6% fuel economy improvement (1).

Lightweight materials, such as aluminium, can reduce the overall fuel consumption of automobiles significantly. However, the primary energy requirement for their production can be greater than that required for ferrous metals. Accordingly, the total energy consumption of the automobile is shifted from the use phase to the production phase. The question is, therefore, which system of materials reduces the total burdens on the environment most throughout the entire life cycle of the product system?

Because material selection affects the entire vehicle life cycle, system analysis tools are essential to achieve aggregate reductions in environmental burdens as well as compare different material groups. Life cycle assessment (LCA) is one such tool that can analyse material alternatives from a life cycle and interdisciplinary perspective. The LCA methodology covers the whole life cycle, from the extraction and production of the raw materials, the foundry processing, the auto use phase and, finally, end-of-life treatment.

In our context, the LCA methodology has been applied to support the choice of materials for a specific automotive component such as a suspension arm. Environmental burdens caused by lightweight metals have been compared with those caused by traditional metals. In particular, global warming potential (GWP), acidification potential, and, air, water and solid emissions associated with specific material groups have been compared to identify the best environmental proposition.

2 AUTOMOTIVE LIGHT-WEIGHTING INITIATIVES

Removing weight to reduce fuel consumption while designing higher performance vehicles is a major challenge confronting the automotive industry. Since the stimulus provided by the energy crisis of the 1970's, there was a 26% vehicle weight reduction between 1976 and 1986. However, in the late 1980's, improved vehicle performance, driving comfort, increased safety and easier maintenance led to a vehicle weight increase of 8% between 1986 and 1992. However, current environmental concerns have returned weight reduction the fore because it offers benefits to consumers and society as a whole. (2)

A number of joint European and North American automobile industry research projects and environmental initiatives are attempting to reduce vehicle weight and, consequently, improve fuel economy. EUCAR, the European automotive industry's research and development body under the umbrella of the European Automobile Manufacturers Association (AECA), is currently working with lightweight materials for vehicles. Environmental agreements with automobile manufacturers are central to the European Union's strategy for reducing CO_2 emissions from new passenger cars. In 1999, the European Commission negotiated a voluntary agreement with ACEA committing automobile manufacturers to reduce the average vehicle emission of CO_2 by 25% by 2008 (3).

Vehicle mass reduction using lightweight materials is one aim of the American Partnership for a New Generation of Vehicles (PNGV). This cooperative research and development program is between the federal US government and several research institutes, automotive suppliers, universities and the United States Council for

Automotive Research (USCAR), whose members are the "big three" US automotive companies, Ford, DaimlerChrysler and General Motors. A principal objective is a 40% vehicle body weight reduction by 2004 (4).

Two approaches to achieve vehicle weight reduction targets are: automotive design and materials selection. The former includes improved aerodynamic design and reduced rolling resistance. For materials selection, the use of lightweight metals and their alloys is the dominant approach.

Replacing ferrous components by those manufactured from lighter metals such as aluminium alloys can substantially reduce vehicle weight. Aluminium offers an ideal engineering solution since its density is one-third that of steel and it satisfies torsion and stiffness requirements. Consequently, aluminium use in passenger cars has grown steadily. Between 1980 and 1994, the aluminium content of the automobile increased by 40% and currently is growing by 4% annually (5). However, aluminium is about five times more expensive than conventional ferrous automotive materials (6). Additionally, the primary energy requirement for the production of aluminium is about ten times that for iron, making aluminium very energy intensive (7).

Concurrent with the development of lighter materials there has been continual improvement in the properties of ferrous materials. The International Iron and Steel Institute (IISI) claims vehicle weight reductions of up to 40% with a "holistic" approach to design using high strength steel (8). The world steel industry has commissioned environmentally focused initiatives offering lightweight steel solutions to the challenges facing automakers. ULSAB-AVC has already achieved the stringent EUCAR and PNGV targets for fuel efficiency and vehicle weight reduction (9).

Finally, it should be noted that economic considerations and recycling issues play an important role in the material selection process and often limit the application of the new lighter materials in the automotive sector.

3 LCA AS A TOOL TO JUSTIFY ENVIRONMENTAL SUPERIORITY

Life Cycle Assessment (LCA) is becoming accepted as the method for determining the environmental performance of automobiles over their entire life cycle. This is expressed by LCA studies and projects to: examine the life cycle impacts of different concepts, processes and materials; determine life cycle costs; and improve automobile design.

These LCA studies can be grouped into different categories according to focus:

- Product-related LCA studies
- Production-related LCA studies
- Concept-related LCA studies
- Full Vehicle LCA studies

Product-related LCA studies are the most common studies and mainly focus on material selection. Several publications (10-13) present LCA studies in which alternative materials were compared to identify the best environmental proposition for a specific automotive component. Thiel et al, (11) performed LCA to compare aluminium and steel in the design of the new Opel Corsa bumper carrier. The study focused on air emissions, specifically, global warming potential (GWP) and concluded that aluminium causes lower greenhouse gas emissions when used for this specific application.

Production-related LCA studies are less common and mainly focus on manufacturing process and end-of-life process selection. Stephens et al (14) performed an LCA study for three aluminium casting processes: lost foam, semi-permanent mould and precision sand casting. They concluded that lost foam casting of automotive aluminium heads and blocks has less environmental impacts than the alternatives.

Concept-related studies have focused on innovative automotive technologies such as studies in which conventional vehicles are compared with new concepts such as electric and hybrid vehicles (15,16). Aoki et al (16) performed an LCA comparing three types of vehicles: the aluminium-bodied hybrid Honda Insight, a simulated steel-bodied Honda Insight and a conventional gasoline vehicle. The LCA study concluded that the hybrid vehicle emitted the lowest CO_2 emissions.

Finally, a number of LCA studies have been conducted on the full vehicle product system. Such studies are intended to estimate the holistic impact of the vehicle product system on the environment. In fact, these studies are Life Cycle Inventory (LCI) studies, the quantitative stage of LCA, since it is too costly and time consuming to conduct such a full LCA. Sullivan et al (17) conducted a review of nine published full vehicle LCI studies and concluded that the use phase is dominant. The use phase is responsible for 60-80% of the life cycle energy consumption and CO_2 emissions. However, for solid waste, the material production phase is dominant and responsible for 60-80% of the total life cycle burdens.

Several automotive companies have applied LCA to the early stages of product development in order to estimate the environmental effects of new automotive concepts or technologies. Mercedes-Benz has applied LCA over 100 product-related studies as well as several for full vehicles as part of its development process (18). Volvo Car Corporation has, since 1998, published environmental product declarations (EPD) for each new car model that present environmental information for consumers on the cars' whole life cycle using information based on individual LCA studies for each model (19)

LCA methodology has also been applied to judge products from an interdisciplinary perspective. For example, BMW Group conducted a LCA study of a side-frame made of conventional steel or Carbon-Fibre-Reinforced-polymer (CFRP) and concluded that CFRP was the best environmental proposition. However, CFRP structural components are currently not regarded as economically recyclable which limits their application (20).

LCA determines all of the environmental burdens associated with an automotive component or even a whole car over the entire life cycle of the product. However, barriers that limit its widespread use include data availability, time and cost constrains as well as inadequate impact assessment methods with inaccessibility to reliable and accurate data the major limitation.

4 DILIGHT PROJECT

A European-funded project with six partners from four countries is developing a new generation of low cost, high performance ductile cast iron for lightweight design of specific automotive components such as suspension components and gear parts. The project is called "New Dispersion Strengthened Low Cost Ductile Iron for Light-Weight Components" (DILIGHT) and, provided that successful results are obtained, weight savings of more than 10% for suspension components and 30% for gear parts may be possible. These savings are comparable with those currently achieved with the use of aluminium alloys but at cost which is only one third of that of aluminium.

However, it is necessary to quantify the potential environmental impacts of the DILIGHT alloy throughout its life cycle and to compare these with competing alloys. Three competing material groups (aluminium, cast iron and the DILIGHT option) will be compared.

The LCA methodology will be applied to assess the environmental aspects and potential impacts of these competing materials. The assessment will consider the whole life cycle of the product system.

5 APPLICATION OF THE LCA METHODOLOGY

The LCA study will compare the environmental life cycle inventory of a specific automotive component made from the competing materials. The assessment will follow the terminology developed by the International Organization for Standardization (ISO) 14040 standards in which LCA is structured within a framework which divides the entire LCA procedure into four distinct phases: Goal and Scope Definition, Life Cycle Inventory Analysis, Life Cycle Impact Assessment and Life Cycle Interpretation (21).

The goal of this LCA study is to compare and contrast the three materials. The objective is to assess the potential environmental impacts of these alternatives and, conclusively, to identify the best material choice in terms of energy consumption, global warming potential and, generally, overall environmental impacts.

Within this paper only aluminium alloy and cast iron have been compared because there is not enough data, at this stage of research, to consider the DILIGHT option.

5.1 Comparability of the Product Systems

The same functional unit has been used in this comparative LCA study: an automotive suspension arm with identical technical specifications. This ensures that the functional unit is well defined and that the alternatives are comparable. The only difference is the weight of the functional unit. It is assumed that the aluminium suspension arm weighs almost 30% less than the cast iron component due to its lower density (22). Table 1 shows the materials and weights of the different automotive suspension arms.

Table 1: Material and Weight of Comparable Suspension Arms

Material	**Weight (kg)**
Aluminium Alloy	1
Cast Iron	1.3

The same criteria have also been used for defining the system boundaries of the comparative product systems. The study was designed as a "*cradle to grave*" LCA study including all the environmental burdens associated with the product systems over the entire life cycle of the suspension arms. However, it was neither possible nor practical to conduct such a detailed LCA study at this stage of the research. Consequently, two of the life cycle stages, manufacturing and assembly and end-of-life management, are excluded due to complete lack of data. Transportation processes between and within the life cycle stages are also excluded from the calculations. Additionally, the foundry process has been covered incompletely since only average figures concerning energy consumption were included in the calculations.

5.2 System Boundaries

The LCA study includes all the processes that contribute significantly to the environmental impacts of the product system investigated. In general, the life cycle of an automotive suspension arm consists of five stages: Material Production, Foundry Process, Manufacturing and Assembly, Auto Use Phase and End-Of-Life Management.

For example, Figure 1 shows the whole life cycle of the aluminium suspension arm.

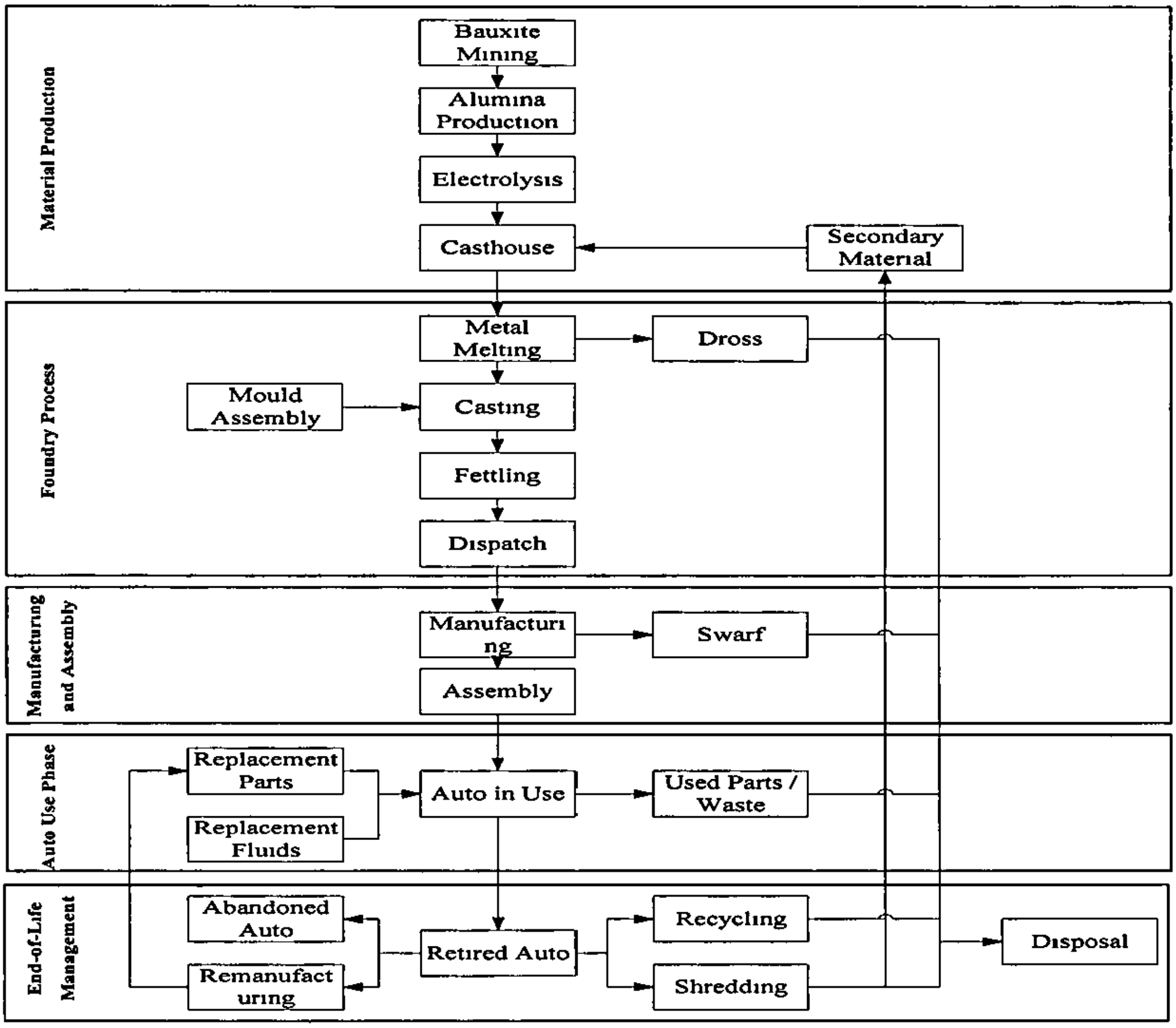


Figure 1: Life cycle of the Aluminium Suspension Arm

It should be noted that the life cycle models, which were used for the LCA, are much more detailed. For example, each square in Figure 1 generally symbolises a whole sub-network of different processes.

5.3 Life Cycle Inventory

A Life Cycle Inventory (LCI) comprises the second part of the LCA study. Mass flows and environmental inputs and outputs associated with the functional unit are calculated, interpreted and presented with the aid of the LCA software tool Boustead Model 4.4.

The LCI results were structured in accordance with the different processes to identify the contribution of each life cycle stage to the total calculated amount. For example, Table 2 illustrates selected air emissions from the different stages of the cast iron product system.

Table 2: LCI Results for the Cast Iron Suspension Arm

Cast Iron	LCI Input	Material Production	Foundry Process	Manufacturing and Assembly	Auto Use Phase	End-of-Life Management	Total
Air Emissions (kg)	CO_2	1.296	2.611	0	19 548	0	23.455
	CO	0.029	0.002	0	0.174	0	0.205
	CH_4	0.001	0.012	0	0.007	0	0.020
	NOx	0.005	0.017	0	0.217	0	0.237

Throughout its product life, the cast iron component contributes 23.4 kg of carbon dioxide emissions, of which 83% derives from the auto use phase, 11% from foundry process and only 6% derives from the material production process.

On the other hand, the aluminium suspension arm contributes 28 kg of carbon dioxide emissions, of which 53% derives from the auto use phase, 36% from the material production and 11% from the foundry process. Table 3 illustrates air emissions from the different stages of the aluminium product system.

Table 3: LCI Results for the Aluminium Suspension Arm

Aluminium	LCI Input	Material Production	Foundry Process	Manufacturing and Assembly	Auto Use Phase	End-of-Life Management	Total
Air Emissions (kg)	CO2	10.123	2.869	0	15.037	0	28 029
	CO	0.004	0.001	0	0.133	0	0.138
	CH4	0.032	0.013	0	0.005	0	0.050
	NOx	0.056	0.018	0	0.167	0	0 241

5.4 Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) examines the product systems from an environmental perspective using impact categories and category indicators connected with the LCI results. Three environmental impact categories were determined in the current LCA study. Every impact category has its own indicator based on an environmental mechanism. The selected impact categories and their indicators are shown in Table 4.

Table 4: Selected Impact Categories and Category Indicators

Environmental Impact Category	**Category Indicator**
Global Warming Potential (GWP)	kg CO_2 Equivalents
Acidification Potential	g SO_2 Equivalents
Photo-Oxidant Formation	g C_2H_4 Equivalents

5.5 Results and Discussion

The life cycle inventories showed environmental and energy differences between the alternative materials. The comparison focused on global warming potential and energy consumption, which comprise the two most important aspects of the LCI results. Finally, the break-even point between the alternative product systems was established.

5.5.1 Energy Consumption

Energy consumption is a principal parameter considered when conducting an inventory analysis of automotive components because much of the emissions, wastes and resources used are associated with the production and consumption of energy or energy carriers throughout the life cycle. The life cycle inventory of energy consumption attributed to the two materials is shown in Figure 2.

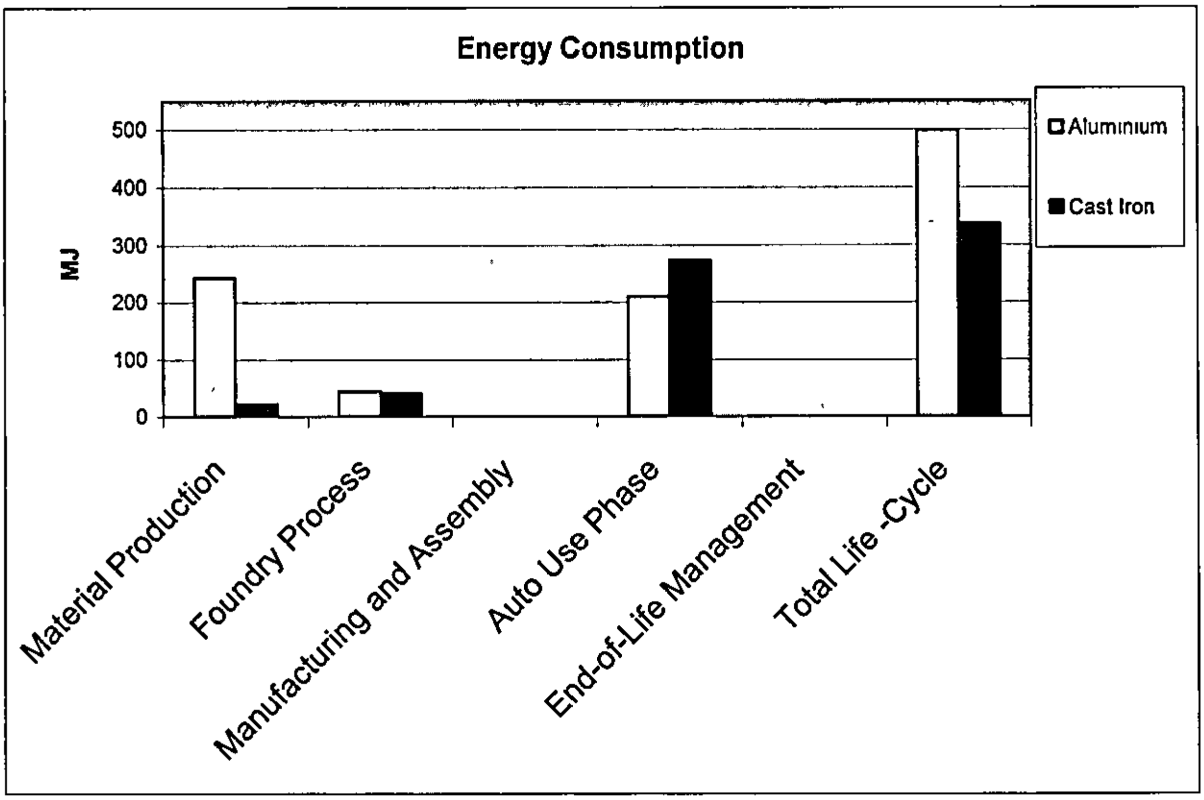


Figure 2: Energy Consumption of the Alternative Material Groups

Figure 2 shows that the total energy consumption is almost 33% higher for the aluminium product system. There is a significant difference between the materials in the production phase since the total energy consumption for aluminium production is about 11 times higher than that for cast iron.

5.5.2 Global Warming Potential

Figure 3 shows that the total global warming potential (29.3 kg of CO_2 equivalents) for the aluminium alloy suspension arm is similar for the material production phase and the auto use phase. For the cast iron suspension arm, global warming potential (24.2 kg of CO_2 equivalents) is clearly dominated by the intensive use of gasoline in the auto use phase due to the effect on fuel consumption of the heavier cast iron component.

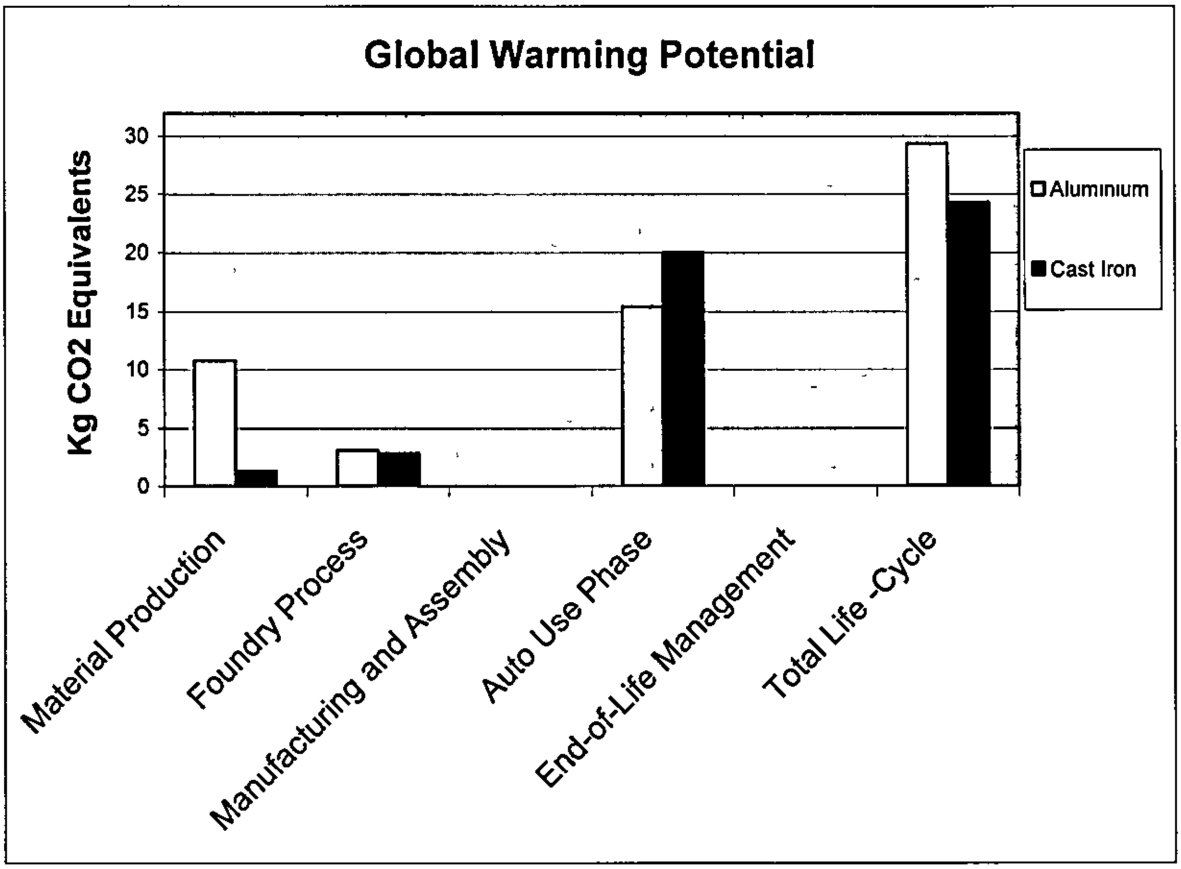


Figure 3: Global Warming Potential of the Alternative Material Groups

Figure 3 also shows that the total GWP is almost 20% higher for the aluminium alloy suspension arm. The major difference between the two materials is apparently concentrated in the material production phase since the GWP for the production of the aluminium component is about 8 times higher than it is for the production of the cast iron suspension arm.

5.5.3 Break-Even Point

Figure 4 illustrates the potential for global warming of the alternative materials in relation to vehicle use. The cast iron component has a clear advantage at the beginning of the curve because of the high-energy demand during the aluminium production phase. Although the gap between cast iron and aluminium is gradually reduced, it takes many kilometres to reach the break-even point, which occurs at about 300,000 km.

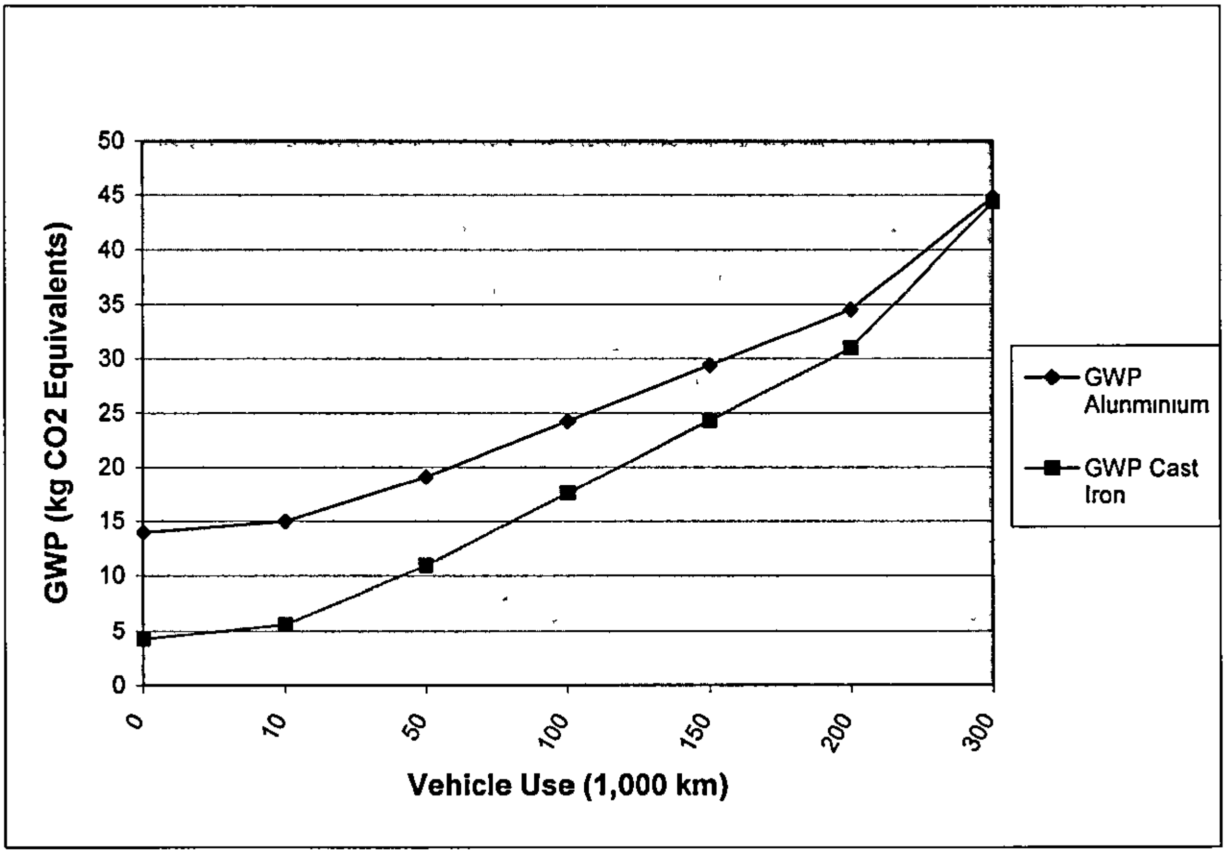


Figure 4: Break-Even Point Between Aluminium and Cast Iron

5.6 Future Work

The next stage of the research will apply LCA methodology to compare and contrast the three alternative material choices (aluminium, cast iron and the DILIGHT option) and, conclusively, identify the best environmental proposition for a specific automotive component such as a suspension arm.

6 CONCLUSION

For the conditions considered, the LCA has shown that the benefits to the environment of substituting aluminium for cast iron are not significant until the vehicle has travelled 300,000 km. This reflects the energy intensity of the process for producing aluminium.

If the new DILIGHT alloy delivers a 10-30% mass reduction without an adverse environmental impact, then this will reduce still further the benefit of using aluminium.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the European Union through a Fifth Framework Programme (GROWTH) contract to conduct research under the contract number: G5RD-CT-2000-00379.

REFERENCES

Jenssen C., Thiel G. (2000). Comparative Life Cycle Assessment of Aluminium and Steel Bumper Carriers. In *Proceedings of the 2000 SAE Total Life Cycle Conference*, April 2000, Detroit, MI, USA, pp.225.

Keoleian G., Kar K., Manion M. and Bulkley J. (1997). Industrial Ecology of the Automobile: A Life Cycle Perspective. SAE. Warrandale, PA, USA.

Commission Recommendation 99/125/EC of 5 February 1999 on the reduction of CO_2 emissions from passenger cars. OJ L 40/49.

Partnership for a New Generation of Vehicles (PNGV). (2003). [Online]. Available: http://www uscar org/pngv/

European Aluminium Association (EAA). (2003). Aluminium in the Automotive Industry. [Online]. Available: http://www.aluminium.org/visuals/downloads/auto pdf

Roth, R, Kelkar, A. and Clark, J. (2001). Automotive Bodies: Can Aluminium Be an Economical Alternative to Steel? In *Journal of Metals (JOM)*, August 2001, pp.28-32.

Moore, C.M., Rohrig, K. and Deike, R. (1999) Auto Aluminium is it really Cost Effective? In *Foundry Trade Journal International*, Vv, pp.37.

ULSAB-Advanced Vehicle Concepts (AVC). (2003). [Online]. Available: http·//www.worldautosteel com/

Peterson, P. (2002). Environment for Green Vehicles, Efficient is Better. In *Designing and Achieving Lightweight Vehicles*. SAE, S-P 1684, pp.11-15.

Saur, K., Fava, J. A. and Spatari, S. (2000). Life Cycle Engineering Case Study: Automobile Fender Designs. In *Environmental Progress*. Vol. 19, No 2, pp.72-82.

Thiel, C., Jenssen, G. (2000). Comparative Life Cycle Assessment of Aluminium and Steel Bumper Carriers. In *Proceedings of the 2000 SAE Total Life Cycle Conference*, April 2000, Detroit, MI, USA, pp.225-231, paper number 2000-01-1495.

Gibson, T. (2000). Life Cycle Assessment of Advanced Materials for Automotive Applications. In *Proceedings of the 2000 SAE Total Life Cycle Conference*, April 2000, Detroit, MI, USA, pp.161-171, paper number 2000-01-1486.

Costic M., Messick, R., Reppe, P. and Keoleian, G. (1998). Life Cycle Assessment of a Transmission Case: Magnesium vs. Aluminium. In *1998 SAE International Conference and Exhibition*, February 1998, Detroit, MI, USA, pp. 137-150, paper number 980470.

Stephens, R., Wheeler C. and Pryor M. (2001). Life Cycle Assessment of Aluminium Casting Processes. In *Proceedings of the 2001 Environmental Sustainability Conference and Exhibition,* November 2001, Graz, Austria, pp.115-140, paper number 2001-01-3726.

Couslon, G., Stobart, R. (2000). Life-Cycle Analysis and the Fuel Cell Car. In *Proceedings of the 2000 SAE Total Life Cycle Conference,* April 2000, Detroit, MI, USA, pp.157-160, paper number 2000-01-1485.

Aoki, K., Hayashi, T. and Kumata M. (2001). Reduction of Life Cycle CO_2 Emissions-The Example of Honda Insight. In *Proceedings of the 2001 Environmental Sustainability Conference and Exhibition,* November 2001, Graz, Austria, pp.17-23, paper number 2001-01-3722.

Sullivan, J., Cobas-Flores, E. (2001). Full Vehicle LCA's: A Review. In *Proceedings of the 2001 Environmental Sustainability Conference and Exhibition,* November 2001, Graz, Austria, pp.99-114, paper number 2001-01-3725.

Finkbeiner, M., Ruhland, K., Cetiner, H. and Stark, B. (2001). Life Cycle Engineering and Design for Environment of the Mercedes-Benz C-Class. In *Proceedings of the 2001 Environmental Sustainability Conference and Exhibition,* November 2001, Graz, Austria, pp.157-164, paper number 2001-01-3730.

Dahlqvist, E., Wendel, A. (2001). LCA Working Procedures when Developing Environmental Product Declerations for Cars from Volvo. In *Proceedings of the 2001 Environmental Sustainability Conference and Exhibition,* November 2001, Graz, Austria, pp.165-167, paper number 2001-01-3731.

Fried, W., Hagen, T. and Wörle, G. (2002). Methods and elements towards sustainable products-BMW's strategy in design for recycling and the environment. In *Design and Manufacture for Sustainable Development,* Professional Engineering Publishing, IMechE 2002, pp 13-27.

ISO 14040. (1997). *Environmental Management. Life Cycle Assessment. Principles and framework.* Geneva: International Organization for Standardization (ISO).

Kalpakjan, S., Schmid, S. R. (2001). Manufacturing Engineering and Technology. New Jersey: Prentice Hall, pp.91.

Appendix XII

This paper presented at the *"2003 International Engineering and Product Design Education Conference"* at Bournemouth University on September 10-11, 2003.

INCORPORATING LIFE-CYCLE ASSESSMENT WITHIN THE TEACHING OF SUSTAINABLE DESIGN

C J Backhouse, A J Clegg, K G Snowdon and T Staikos

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, LE11 3TU, UK

ABSTRACT

The Wolfson School of Mechanical and Manufacturing Engineering at Loughborough University has received support from The Royal Academy of Engineering to develop and implement teaching that supports the concept of 'Engineering Design for Sustainable Development'. The paper describes the development of two teaching modules that support this concept with particular emphasis on the incorporation of LCA. The first module entitled 'Engineering Design for Sustainable Development' was developed as an intensive, one-week module for the Wolfson School's long-standing postgraduate MSc course in Engineering Design. The second, entitled 'Sustainable Product Design', was developed exclusively for the final (fourth) year of a MEng degree in Product Design and Manufacture. The paper summarise the teaching and learning experiences associated with the incorporation of LCA in the modules and provide guidelines for those teachers who would like to incorporate LCA in their courses.

1 INTRODUCTION

The Royal Academy of Engineering awarded a Visiting Professorship in Engineering Design for Sustainable Development to Loughborough University in 1999. Originally for three years, the RAE support has been extended for a further two years and so is currently in the fourth year of the five-year programme. The objective of the scheme is to encourage university engineering departments to appoint visiting professors that can transfer their industrial knowledge and expertise to the departments' teaching staff and students.

1.1 The Wolfson School

The Wolfson School of Mechanical and Manufacturing Engineering was formed in 2000 by the amalgamation of two established departments, Mechanical Engineering and Manufacturing Engineering, and makes up approximately one third of the Faculty of Engineering at Loughborough University. The School offers four undergraduate programmes:

Mechanical Engineering MEng/BEng
Manufacturing Engineering and Management MEng/BEng
Product Design & Manufacture MEng/BEng
Sports Technology BSc

The BEng and BSc programmes are of three years duration and the MEng is of four years. Students can add an industrial placement year between the second and third academic years to gain an additional Diploma in Industrial Studies. The School has a current undergraduate population of approximately 715.

The School also provides taught postgraduate MSc courses in:

Engineering Design
Manufacturing Management
Mechatronics
Engineering Management
Engineering Design and Manufacture

The School's postgraduate taught course population is approximately 40 full-time and 160 part-time students.

1.2 The Royal Academy of Engineering

The Royal Academy of Engineering (RAE) is committed to a long-term programme to encourage the effective application of engineering to improve the environment, to promote sustainable development and to protect natural resources. The RAE operates a highly successful scheme of Visiting Professors in Principles of Engineering Design that seeks to develop relationships between universities and engineers in outside organisations to enhance the learning experience for students. The success of this scheme led to the introduction, in 1998, of a scheme specific to Engineering Design for Sustainable Development. In 1999, Loughborough was able to appoint a Visiting Professor who held an appointment as Manager of Eco-design at Nortel Networks, a major multi-national, tele-communications equipment company. His objective was to work with the Wolfson School's academics to transfer knowledge and expertise to the staff and students.

1.3 Product Design and Manufacture

Product Design and Manufacture (PDM) is concerned with the creation of tangible and usable artifacts to meet a wide range of customer needs and requirements. It is the process by which ideas are converted into products. The programme is designed to provide industry with graduates possessing the skills and knowledge needed for the creation of successful world-class products. It is one of the few courses of its type to be accredited by both the UK Institution of Mechanical Engineers and the Institution of Electrical Engineers (Manufacturing Division) The subjects taught in Product Design are wide-ranging. As well as engineering science, design methodology and manufacturing, the topics of ergonomics and aesthetics in product design are covered. The theme of design is used to draw together subject areas and show their relevance in the creation of new products.

1.4 MSc in Engineering Design

The availability of well-designed products, processes and systems to meet the need of the market is the foundation of successful commercial enterprises. The programme in Engineering Design provides formal and practical education to meet the needs of the design activity in today's competitive markets. The objective of the programme is to provide a course of study that will enable the student to work effectively in an engineering design role, regardless of whether that role is concerned with the design of products, processes or systems at an overall or detail level. The programme consists of eight, week-long, taught lecture modules plus project work. Each module is self-contained, and covers a complete design-related topic. The list of modules follows:

- Engineering Design Process and Project Management
- Engineering Design Methodologies
- Engineering Design Management and Business Studies
- Computer Aided Engineering
- Industrial Design and Human Factors
- Structural Analysis
- Materials Selection for Designers
- Engineering Design for Sustainable Development

2 SUSTAINABLE PRODUCT DESIGN

Sustainable Product Design (SPD) was developed exclusively for the final (fourth) year of a MEng degree in Product Design and Manufacture. This compulsory module was taught for the first time in semester 2 of the current academic year. Students registered for this module had already taken a module entitled 'Manufacturing for the Environment' in the third year of their course. The module was taught by a combination of lectures, case studies and a group project. Assessment was by a combination of a formal examination and the group project report, the latter constituting the coursework element for the module. The students were taught to use the Boustead LCA software tool and they were required to use it to support their selection of materials for the group project activity.

SPD deals with the elementary demand, essential product functions, the systems in which the products function; the nature, availability and selection of resources; and the distribution of those resources among nations and generations (1). It encompasses the concepts of ecodesign and design for the environment. However, SPD should be more than just environmental optimisation of products and services. It should also attempt to incorporate moral, ethical and social considerations because sustainability encompasses social and economic dimensions as well as resource conservation and the environment.

The module was developed to provide PDM students with an understanding of the tools and techniques available to facilitate SPD. It is also intended to provide knowledge of the product design processes that can reduce environmental impacts and promote sustainable practices. The contents of the syllabus include: SPD, DfE, LCA, quantitative and qualitative design guides, producer responsibility legislation, case studies, and project oriented activities. The group project ensures that the students apply the knowledge gained on a real industrial redesign project.

3 ENGINEERING DESIGN FOR SUSTAINABLE DEVELOPMENT

Engineering Design for Sustainable Development was developed as an intensive, one-week module for the Wolfson School's long-standing postgraduate MSc course in Engineering Design. However, the module is not exclusive to this course and accepts students from both within and outwith the School. The module operated in February 2003 with 42 registrations. The module is intended to provide students with an understanding of the environmental pressures acting on design to manufacture businesses and the scope that designers have to reduce the environmental impact of products throughout their life-cycle. The module consists of 35 hours of contact time that include industrial presentations, and case studies that are intended to provide students with an understanding of the practice of 'Design for the Environment'. Assessment is by examination and coursework with a mark distribution of 80% and 20% respectively. The module content includes: human impact on the environment; sustainable development; environmental legislation; materials & energy resource conservation; waste management; life-cycle assessment; design for environment;

sustainable product design; case studies from the automotive, aerospace and white goods sectors; and business and environmental management issues.

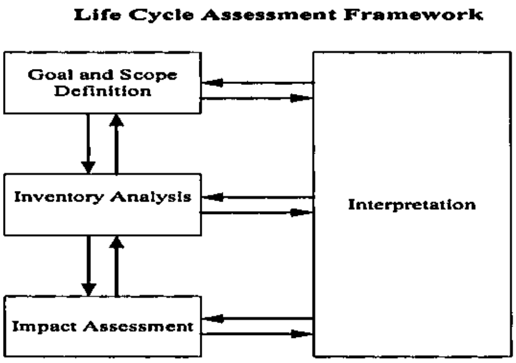
4 LIFE-CYCLE ASSESSMENT

Life-cycle Assessment (LCA) attempts to assess the environmental impacts at each stage in the life-cycle of a product (2). LCA thus considers:

- Extraction and processing of raw materials.
- Manufacture of the product (and associated packaging and/or consumables).
- Use.
- End-of-life options (reuse/recycling/disposal).

By quantifying these impacts, LCA provides an objective basis for design choices between alternative materials/processes/products or systems. It is not suggested that the designer should conduct the assessment, but rather that the designer be provided with LCA output data that supports the choice between alternatives. An internationally agreed standard for LCA has been published by the International Organisation for Standardisation (ISO) and is documented in the ISO14040 series. The recommended methodology consists of four stages:

Definition of the goal and scope.
Life-cycle inventory analysis.
Life-cycle impact assessment.
Life-cycle interpretation.



4.1 LCA Teaching in Sustainable Product Design

LCA is taught in two formal sessions. The first is a two-hour lecture/tutorial combination that introduces and defines the methodology and requires the students to practice elements of the methodology. The second session is a two-hour demonstration/tutorial that introduces the students to the Boustead Model and software and then requires them to develop their skills in using the software for scenarios.

The Boustead Model and software was available within the School because it had been purchased to support a research contract. The cost of the software, the licence to operate it on four machines and the training totaled approximately £2250.

These skills must subsequently be applied in DfE group projects in which the students must demonstrate the use of the LCA software to substantiate a choice between alternative materials The students work in groups of three to undertake the DfE project. In the current year the artifacts considered were supplied by Jaguar Cars Ltd. and a representative from the Company briefed the students on their task. The artifacts consisted of a laminated fuel tank with appendages, an external bumper cover/assembly and a sun visor.

The tutorial questions helped students to consider goal and scope formulation, functional units, flow diagrams and to compare the impacts of alternative choices (using data sets rather than software). Students worked in their project groups to conduct the tutorial exercises.

The steps in the Boustead LCA software are:

1. Construct a reliable and detailed flow diagram of the sequence of unit operations that form the system of interest.
2. Collect input and output data for every unit operation.
3. Enter the data into the Boustead model.
4. Calculate the data.
5. Read the data.
6. Determine values for environmental effects.

Following the introduction to the Boustead software the students gained experience in its use by considering a number of scenarios. These included oxygen production in the UK; bauxite mining in Australia; production of 1 kg of dry sand in the UK; silicon carbide production and an industrial process in the UK.

The students were asked to provide feedback on the LCA software training activity by scoring from 1 to 5 the four aspects shown in Table 1. The table also shows the overall average response score.

Table 1: LCA Activity Feedback

Aspect	Score
New knowledge gained	4.44
Intellectual challenge	3.78
Interest value	4.56
Enjoyment value	4.00
Overall average response	4.20

4.2 LCA Teaching in Engineering Design for Sustainable Development

Time tabling constraints required that LCA be taught by a combination of a formal introductory lecture complemented by a case study. This section briefly describes the LCA case study that was based on Nortel Networks experience in the assessment of LCA software packages. It requires that students evaluate the alternative choices of aluminium alloy or polymer for use in the faceplate (front cover) for a rack containing telecommunications equipment.

4.2.1 Nortel Networks Faceplate LCA Case Study

The case study evolved from a Nortel Networks investigation to evaluate two software tools for conducting LCA. The software tools were the Boustead Model and the PIRA International Model. 'Look and Feel' panels were selected for the LCA exercise. These panels are used as faceplates for the sub-racks of equipment for PCB support, ESD and MMI/FRI shielding, and structural integrity in Transport Node Switches. Two material choices were considered: aluminium alloy and plastic. The faceplates were chosen because they represent a relatively simple part in terms of construction and materials.

The functional unit chosen for the exercise was a 16 inch (406.4 mm) wide sub-rack of equipment with an appropriate number of panels filling the space. The number and size of panels for a standard sub-rack was established and this mix of panels was specified as the functional unit. This produced total weights of 967.9 g and 686.7 g for aluminium and plastic respectively. The aluminium panels were produced as extrusions and the plastic panels were injection moulded from a polymer blend with a phosphorus compound flame retardant and titania and carbon black pigments to produce a final grey colour. The plastic panels were selectively electroless plated on their inner surfaces.

4.2.2 Nortel Networks Experiences in the Use and Limitations of LCA

Databases are still evolving to incorporate new data as it is generated for specific processes. If an exact fit is not possible, a compromise may be necessary. For the LCA tools used, it was necessary to treat the aluminium as ingot rather than an extrusion. Similarly, as the data for the particular polymer blend was not available in either database, an alternative was specified for the purpose of the exercise.

5 EXPERIENCES

The undergraduate students had received an introduction to LCA in the compulsory third year Manufacturing for the Environment module. However, the SPD module required that they develop expertise in both LCA methodology and in the use of LCA software. The SPD module activities were intensive but appropriate to able MEng students. It is not suggested that this relatively short introduction enabled the students to master the complexity and detail of the Boustead Model and software. However, the requirement to use the software during their group project phase extended the students' experience in the understanding and use of the LCA software. This phase was complemented by extended tutorial support from a member of staff skilled in the use of the software. The size of the group is clearly important in terms of the commitment of resources and availability of support. With a module group of only nine students, this was relatively easy to manage.

The time available to present the LCA topic to the MSc group was somewhat less than that available to the MEng students and the former did not have the benefit of an introduction to the topic in an earlier module. The approach adopted for the MSc students included an introductory lecture followed by an industrial case study to demonstrate a practical experience in the use of LCA. This approach enabled the benefits and limitations of the LCA approach to be successfully demonstrated.

6 CONCLUDING SUMMARY

The paper has described how life-cycle assessment is being incorporated within two modules that support the teaching of environmental and sustainable development principles within the Wolfson School's undergraduate and postgraduate course portfolios. LCA is an important tool for quantifying certain environmental impacts and for providing the basis for an objective comparison between alternative choices. However, LCA tools are expensive to purchase and operate and they have limitations. It was not intended that the teaching of LCA described in the paper produce skilled LCA practitioners but rather that the students become aware of how LCA is conducted and the limitations of the process. It is most likely, certainly in larger organisations, that designers would be provided with DfE tools that suggest preferred choices of materials. Those choices would have been determined by LCA conducted by specialists either within the organisation or based in external consulting organisations.

7 ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the Royal Academy of Engineering and the financial and practical support of the Directors of Nortel Networks.

8 REFERENCES

1. Design + Environment: A guide to greener goods. H Lewis and J Gertsakis, Greenleaf Publishing, Sheffield, 2001.

2. Sustainable Solutions: Developing products and services for the future Editors: M Charter and U Tischner, Greenleaf Publishing, Sheffield, 2002.

Appendix XIII

This paper presented at the *"2003 Business Strategy and Environment Conference"* at Leicester University on September 16, 2003.

Reducing the Environmental Impacts of Metal Castings through Life-cycle Management

C J Backhouse, A J Clegg and T Staikos

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leics, LE11 3TU, UK

Abstract

Metal castings are fundamental to our technological way of life, from the ubiquitous mobile telephone to the internal combustion engine. Their production requires the consumption of materials and energy and the output of waste. However, the impact of castings extends far beyond their production. A reduction in casting weight, through material property enhancement and improved design, positively impacts the whole life cycle. Reducing a casting's weight not only reduces the foundry's environmental impacts but also, the demands for raw materials and energy inputs and, if that lighter casting is used in a transport application, fuel consumption and carbon dioxide output associated with the use phase.

The context of the paper is established by considering the issues from the perspectives of industrial ecology and supply chain management. It then refers to the use of LCA to identify the environmental costs, benefits and opportunities associated with research to develop an improved material for automotive castings. This ferrous material delivers improved properties that may provide sufficient weight reduction to counter the need to substitute iron by aluminium. This could address the concerns that, in the case of the automobile, an extended use phase may be necessary before the adverse environmental impacts of producing aluminium are offset by reduced fuel consumption during the use phase.

The preliminary LCA suggests that the use of secondary material (i.e. recycled material) is essential if the lower density of aluminium is to provide life-cycle energy saving benefits for a component used in an automobile. The distance that a car must travel before the reduced mass of aluminium begins to provide a reduction in the life cycle energy consumption is 300,000 km for the scenario in which only primary materials are used. This distance is reduced to 150,000 km when a combination of 50% primary and 50% secondary material is used.

Introduction

The automotive industry is one of the largest and most complex industrial sectors on a global scale. It typically contributes 4 to 8% of GDP and employs 2 to 4% of the labour force in an OECD country [1]. In the EU, some 1.2 million people are employed in jobs that are directly related to vehicle manufacture with another 12 million employed in jobs that are indirectly related to this specific sector. Numerous adverse environmental effects are associated with the life cycle of motor vehicles. One of the most serious concerns is the consumption of non-renewable energy resources during the whole life cycle but especially during the use phase. Since the combustion of fuels generates carbon dioxide, road transport is a significant contributor to global warming effects. It has been estimated that road transport accounts for 22% of the total carbon dioxide emissions in the EU and that this contribution grew by about 9% from 1990 to 1997 [2]. With such emissions projected to continue to increase in Europe up to 2010, it is not surprising that the industry is subject to continuing market and regulatory pressures to improve its environmental performance. Vehicle mass is the single most important factor in improved fuel economy since a 1% reduction in vehicle mass yields a 0.6% fuel economy improvement [3].

Industrial Ecology

Industrial ecology, as applied in manufacturing, involves the design of industrial processes and products from the dual perspectives of product competitiveness and environmental interactions. The systems-oriented vision accepts the premise that industrial design and manufacturing processes are not performed in isolation from their surroundings, but rather are influenced by them and, in turn, have influence on them [4].

Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimise the total materials cycle from virgin materials to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimised include resources, energy and capital

The overall objectives of industrial ecology are to minimise the input of limited resources and minimise the output of waste. Waste is considered to be anything that does not add value. Figure 1 presents a schematic view of industrial ecology [4].

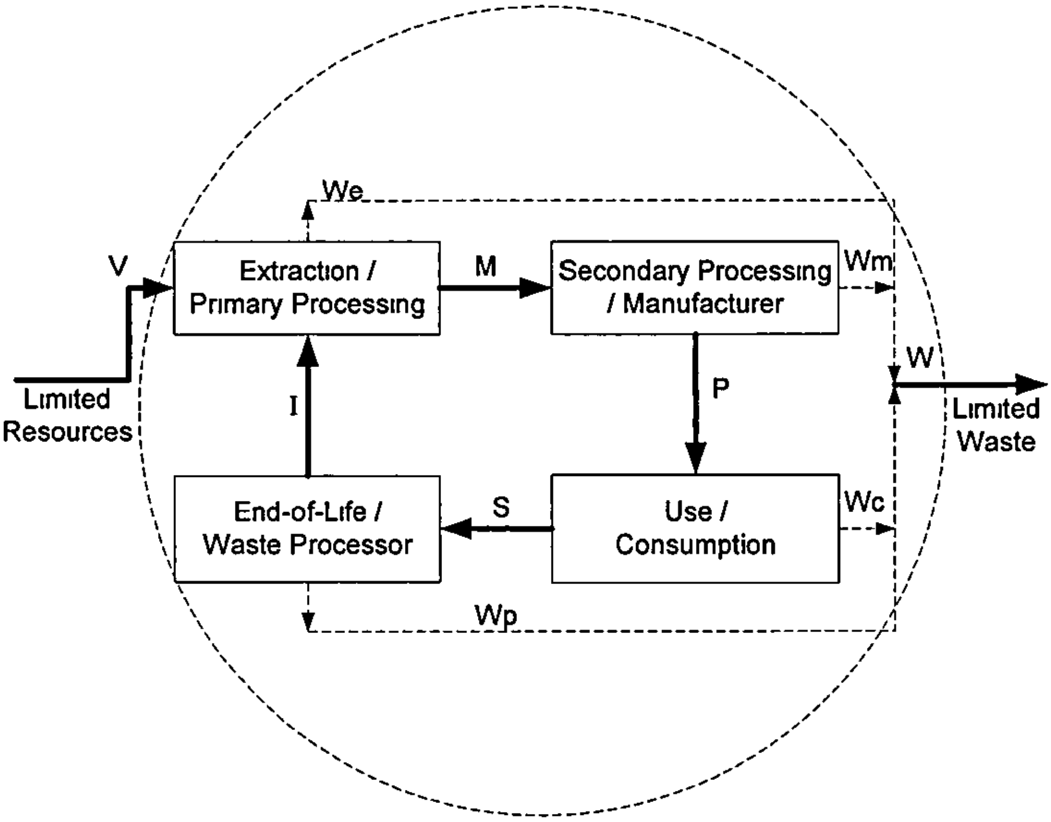


Figure 1: A Schematic Representation of Industrial Ecology [4].

Within each operation we need to maximise efficiency by minimising waste, for example by practicing internal recycling and closing loops. We also need to minimise consumption, especially in the use/consumer phase. This means reducing the volumes of material contained within a product (i.e. dematerialisation) and minimising the consumption of consumables. The role of product design is important here. Any reduction in materials, i.e. dematerialisation, reduces resource consumption and waste in the preceding stages. The letters in figure 1 refer to the following flows. V, virgin material; M, processed material; P, product; S, salvaged material; I, impure material; and W, waste.

Supply Chain Management

Few product producers are vertically integrated to the extent that they produce all of the materials and components that they use in their products. Most companies purchase their materials/components from first tier suppliers who in turn purchase inputs from secondary and tertiary tier suppliers. This is important because it adds complexity to the supply chain and it can dilute the influence and performance of an environmentally pro-active business. However, by consuming less through improved and efficient product design the product producer can effectively impose resource conservation on the supply chain.

With the advent of EU 'producer responsibility' legislation the producer is encouraged to take an even greater responsibility for both life cycle and supply chain management issues. For example, a car producer faced with responsibility for the collection of cars at the end-of-life may need to distribute materials and components to the supply chain constituents that produce and provide specific materials or components. Steel body shells to the steel producer, redundant castings to the foundry, re-usable components to the correct supplier for quality assessment and refurbishment as required.

Review

Foundry Mass Balance

The UK foundry industry produces around 1.3 million tonnes of castings/annum for a diverse range of products and in a diverse range of metal alloys. Castings are used in a very wide variety of applications that include automotive, water distribution, fluid transmission, energy and aerospace industries. The industry is subject to the same environmental legislation with particularly relevant examples being the Landfill Tax and the Climate Change Levy. The Foundry Mass Balance (FMB) [5] calculated that approximately 4.5 million tonnes of direct inputs were required to produce 1.3 million tonnes of castings/annum. This input included 1.8 million tonnes of water.

The foundry industry is already quite effective in its recovery, reuse and recycling of two of its principal inputs: metal and sand. Nevertheless, solid waste, which represents about 14% of the output side of the mass balance, is dominated by waste sand. Most of this waste sand goes to landfill and because it is classified as inactive waste it is taxed at the lowest level. A number of successful initiatives have been introduced to stimulate the beneficial reuse of foundry wastes. For examples, waste sand may be used as a concrete additive, for road bedding or for mixing with asphalt for road surfacing. However, in the context of this paper it is the issue of energy consumption and its impact on carbon dioxide generation and global warming that is of most interest.

It was estimated [5] that the foundry industry consumed approximately 3.5 million MWh of energy in the year 2000. This produced 1.12 million tonnes of carbon dioxide, of which about 40% was produced directly by the foundry industry with the balance being output from electricity generation.

Foundries and Energy Consumption

The industry is a significant user of energy and, not surprisingly, melting and holding of metal is the major consumer of energy in the iron sector which accounts for 80% of the foundry sector's use [6]. Whilst melting and holding account for the major part of consumption, between 20 and 50% (average 35%) of a foundry's energy consumption is related to 'services'. These services comprise motors and drives, compressed air, lighting, space heating etc. Whilst it always makes sense to target the major consumption of energy first in the drive to reduce consumption, other areas should not be neglected.

The pressure to reduce the weight of castings comes from customers because reducing the weight reduces the cost and because a reduction in the weight of the final component reduces the energy required for moving it. Dematerialisation, realised by product design, that reduces the mass of a component produced as a casting will reduce the consumption of energy in the foundry. Lighter components not only require less metal to be melted but also require less of the service inputs. Process yield is an important concern. It is not unusual for process yield to be less than 60%, i.e. the mass of castings produced divided by the mass of metal poured. This inefficiency arises from the need to provide channels to direct the metal into the mould and the need for feeders (reservoirs) of molten metal to compensate for the physical phenomenon of contraction associated with the transition from liquid to solid metal. There is a correlation between the mass (particularly the heaviest section) of a casting and the yield. Lighter castings require less feeding so that the mass of metal processed to produce that lighter casting is reduced.

In 1996 it was estimated that the UK non-ferrous casting sector produced 210,000 tonnes of castings of which 150,000 tonnes were of aluminium alloys [7]. It was estimated that the output of aluminium alloy castings was increasing at the rate of 5 to 6 % per annum. This was partly due to the substitution of iron castings in automotive applications. It was estimated that melting and holding each accounted for 30% of the energy consumed with the balance for support services.

It is estimated that some 7500 tonnes/annum of aluminium is 'irredeemably lost' through dross, spillage and machining losses. Apart from its value (£8million) it contains some 1.3 PJ of primary energy. The overall cost of energy/tonne of good castings was estimated to be £130.00 (for a consumption of 42.6GJ).

LCA Project

The DILIGHT (the acronym for a project entitled New Dispersion Hardened Low Cost Ductile Cast Iron for Light Weight Components) project aims to develop a new generation of low cost, high performance ductile cast iron for lightweight design of automotive components such as suspension or gear parts. Providing that projected properties are realised in the new alloy, weight savings of between 10 and 30% may be possible. Such weight savings could restore the competitiveness of iron castings over aluminium castings in both economic and environmental terms. This paper concentrates on Loughborough University's role in the DILIGHT project. This role requires that Loughborough conduct life-cycle assessments of cast iron and aluminium alloys and then compare the data with that from an LCA to be conducted on the new DILIGHT alloy.

Materials selection affects the entire vehicle life cycle and, because of this, a systems analysis tool is essential if the goal is to achieve aggregate reductions in environmental burdens. LCA is such a systems analysis tool that can be used to assess the environmental aspects and potential impacts associated with all the stages in a product system.

Methodology

The Boustead LCA Model software was chosen for the project. This choice was influenced by its use by a research partner and by the need for compatibility. The ISO14040, 1997 LCA framework, shown in figure 2, was adhered to. For the purpose of the initial analysis a fictive automobile suspension component was chosen as the functional unit and allocated a weight of 1 kg in aluminium alloy. The equivalent weight of this component in cast iron was assumed to be 1.3 kg.

Two scenarios were considered. In the first it was assumed that the metal to be converted into castings was primary material, i.e. pig iron from the blast furnace for the cast iron and aluminium ingot from the smelter for the aluminium castings. In the second scenario it was assumed that the metal converted into castings comprised 50% primary and 50% secondary material. The term secondary material is used here to denote recovered and recycled material. The LCA analysis provided output data on selected air emissions, energy consumption and global warming potential and selected output is presented in the results.

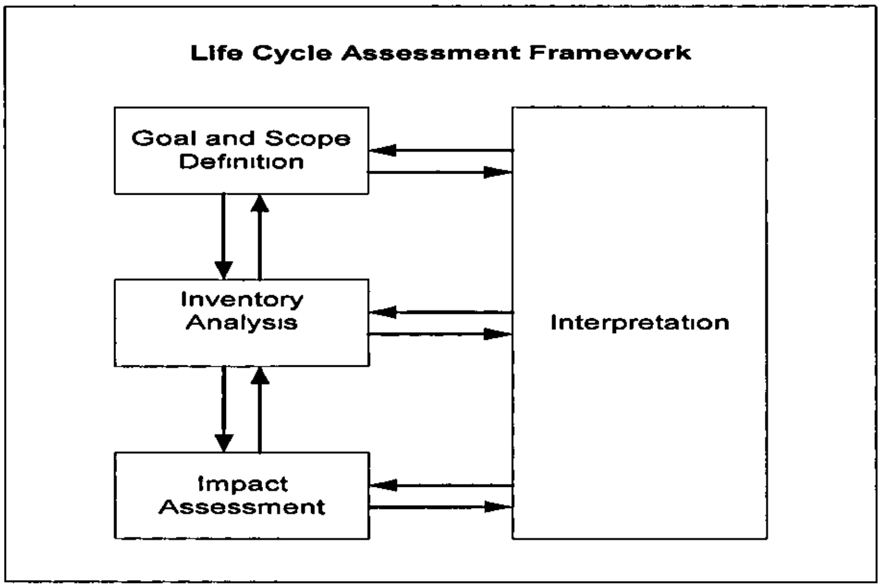


Figure 2: The ISO 14040, 1997 LCA Framework

The life cycle of the product system was assumed to consist of the following five life cycle stages:

- Material production (primary and secondary)
- Foundry processing
- Manufacturing and assembly
- Automobile use phase
- End-of-life management

The system boundary for the life cycle of an aluminium suspension arm is shown in figure 3. The initial LCA was restricted to the three life-cycle stages considered to have the most impact on the environment, namely the material production, foundry processing and automobile use stages. Data for the LCA studies derived from literature sources and research partners.

Results

The relative values for energy consumption for the two product systems, assuming 100% primary material inputs, are shown in figure 4 and the related global warming potential (GWP) data in figure 5. The output from the LCA model produced a total life-cycle inventory of greenhouse gases of 29,3 kg (CO_2 equivalents) for the aluminium suspension arm. This figure was dominated by the intensive consumption of gasoline in the automobile use phase (15.4 kg of CO_2 equivalents). Consequently, the automobile use phase accounts for 52% of global warming potential. The material production phase contributes 37% and the foundry processes the remaining 11% over the life cycle of the product system. For the equivalent cast iron component the total greenhouse gases are 24.2 kg of which the foundry process contributes 12%, the material production 6% and the use phase 82%

Similar data were generated for the 50% primary + 50% secondary material scenarios and, as would be expected, the values for material production, the auto use phase and the total life cycle were substantially lower.

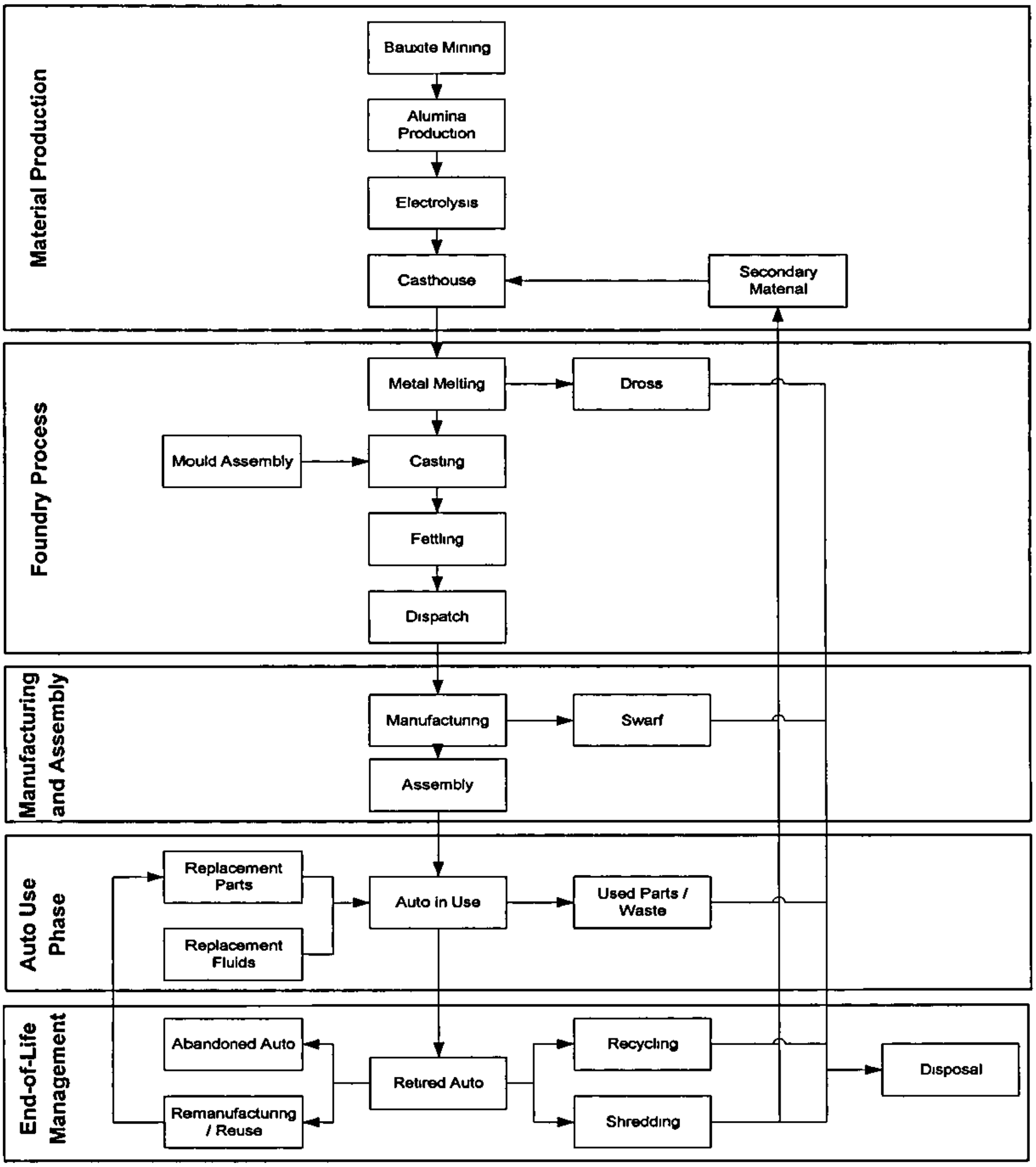


Figure 3: A Shematic Representation of the Life-cycle Stages for an Aluminium Suspension Component

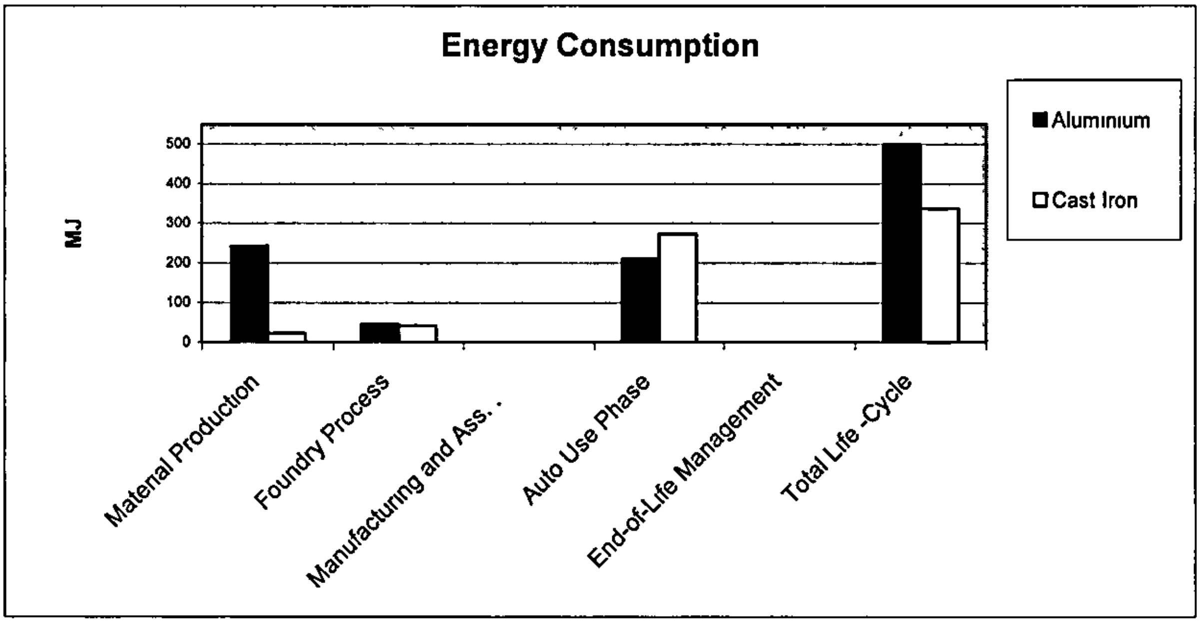


Figure 4: Life-cycle Energy Comparison for Aluminium Vs Cast Iron

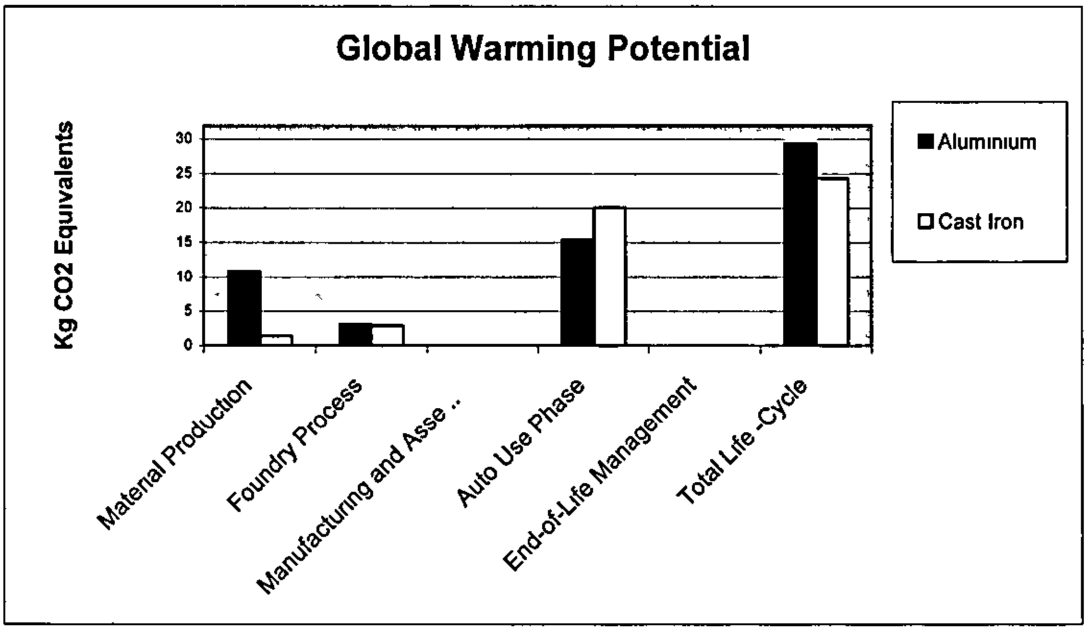


Figure 5: A Comparison of Global Warming Potential for Aluminium Vs Cast Iron

Discussion

For the purposes of this evaluation the functional unit was assumed to have a mass of 1 kg in aluminium alloy and 1.3 kg in cast iron. On a mass for mass basis, based on densities of 2.7 and 7.86 g/cm^3 for aluminium and iron respectively, the density difference is almost 300%. However, because of the difference in mechanical properties of the two metal alloy systems, it is rarely possible to realise the full potential for weight saving [8].

The preliminary LCA has raised some interesting issues. The fact that a lighter vehicle will reduce its fuel consumption and therefore its carbon dioxide emissions and global warming potential is not disputed. However, the question to be asked is whether this benefit transfers to all stages in the life cycle. There are two issues that must be separated: dematerialisation and material substitution. By dematerialisation we mean a reduction in the mass of the component by improved design. The material of choice does not change. However, in materials substitution we seek to reduce the mass of a component by choosing a material of lower density. In both cases we may achieve our objective of reducing mass, improving use phase fuel efficiency and reducing use phase global warming effects. However, we should not assume that the benefit automatically transfers to all life-cycle stages. The effect of dematerialisation should translate to most life-cycle stages since the benefits of using less material transfers back along the supply chain to primary material production. Similarly, benefits should arise at the end-of-life stage if there is less material to handle and process. However, we cannot assume such benefits when we substitute a lighter material because the processing requirements are changed. This is epitomised by the substitution of iron by aluminium. Firstly, one must recognise that the mass reduction benefit of substitution is not directly proportional to the density difference and secondly that the primary processing of aluminium is significantly more energy intensive.

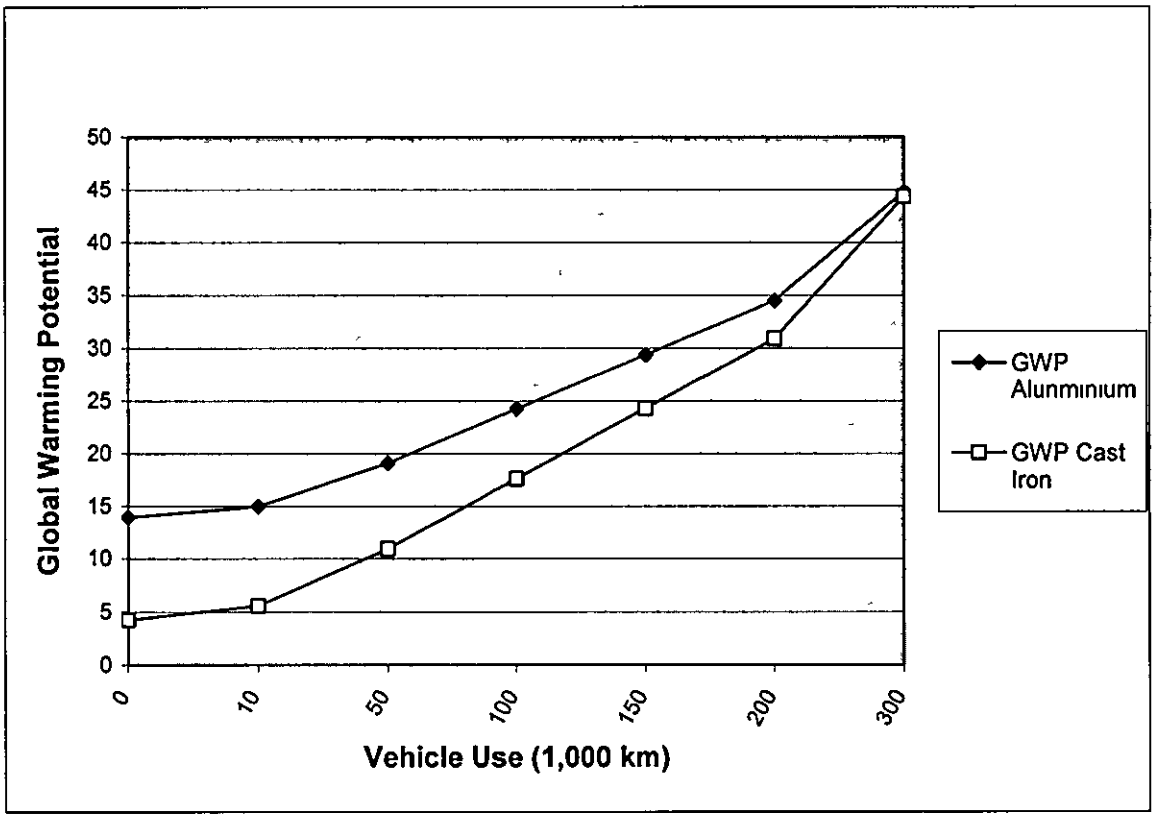


Figure 6: The Break-Even Point for Primary Aluminium Vs Primary Cast Iron

This issue is demonstrated by these LCA results. When the life cycle effects of using primary materials are considered, see figure 6, we can see that the benefit of reduced fuel consumption when using aluminium is not realised until a distance of 300,000 km has been exceeded. This demonstrates the very significant influence that primary production has on energy consumption and global warming. In practice, most cast components would be produced using a mixture of primary and secondary materials. Whilst there is a reduction in processing energy for both materials, the effect is most dramatic for aluminium. If we now compare the life cycle effects, see figure 7, we see that the benefit of reduced fuel consumption in the use phase by using aluminium is realised after 150,000 km.

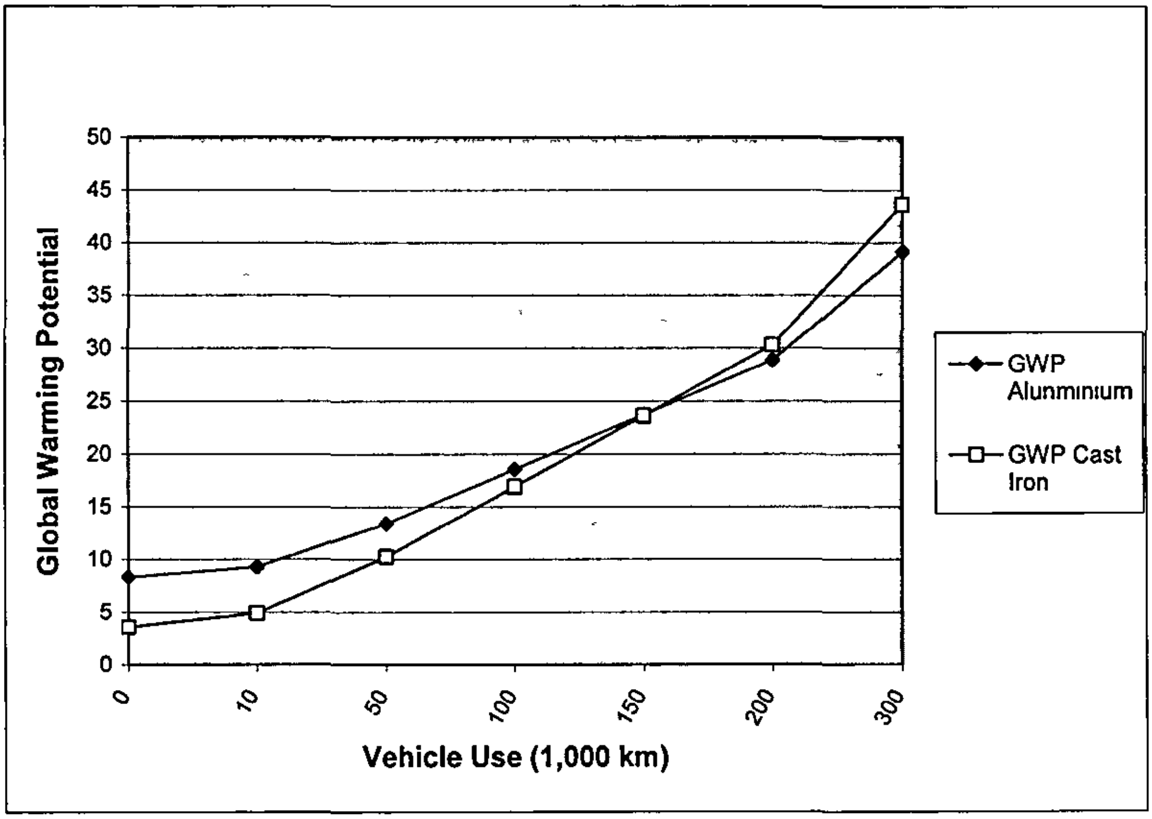


Figure 7: Break-Even Point – 50-50% Recycling Scenario

The benefit of using secondary aluminium could be extrapolated: the greater the proportion of secondary aluminium used to produce the cast automobile component, the lower will be the life-cycle impact. Naturally, one should not forget that the availability of secondary material is dependent upon there being primary material to begin with. However, what it does demonstrate is the value of effective and efficient recycling that enables aluminium to be recovered and reprocessed to ensure that the use of secondary material is maximised.

Summary

As a constituent of the supply chain to the automotive industry, foundries have an important role to play in the quest to reduce energy consumption and associated carbon dioxide emissions. This role can be independent of the supply chain, i.e. by maximising material efficiency and minimising both energy consumption and waste production. The industry can do this by applying industrial ecology principles and by seeking beneficial reuse opportunities for those materials that it would normally consign to landfill. The industry can also support the whole life cycle by the application of technology and material developments that reduce the volumes/mass of material processed in the form of castings. The dematerialisation of a cast component benefits the upstream phase of the life cycle and supply chain by reducing the demand for material processing. It reduces the downstream impacts by reducing the energy consumed to move the cast components, i.e. by reducing fuel consumption during the use phase of the automobile. The direct substitution of a light metal such as aluminium for a heavy metal such as iron may not have the positive environmental benefit that the reduced fuel consumption figures alone might suggest. There is clearly benefit to be derived by reducing the mass of iron components by developments such as those sought in the DILIGHT project.

Conclusions

For a system in which primary aluminium competes with primary cast iron to generate a mass saving of 23%, the demand for energy for the aluminium product system is 33% higher than it is for the alternative cast iron product system. This in turn generates a global warming potential that is 20% higher.

For a system in which a combination of 50% primary and 50% secondary material is used, the demand for energy for the aluminium product system is reduced.

The distance that a car must travel before the reduced mass of aluminium begins to provide a reduction in the life cycle energy consumption is 300,000 km for the scenario in which only primary materials are used. This distance is reduced to 150,000 km when a combination of 50% primary and 50% secondary material is used.

Acknowledgements

The authors acknowledge the support of the European Union through a Fifth Framework Programme (GROWTH) contract to conduct research under the contract number: G5RD-CT-2000-00379. They also acknowledge the agreement of the partners in the contract to the publication of this paper.

References

[1] UNEP, Report on the Automotive Industry as a Partner on Sustainable Development, Geneva, 2002, pp 12.

[2] European Commission. CO_2 Emissions from Cars. The EU Implementing the Kyoto Protocol. Luxembourg: European Commission. 2000

[3] Jenssen, C. and Thiel, G. Proceedings of the 2000 SAE Total Life Cycle Conference, April 2000, Detroit, MI, USA, p225-231.

[4] Industrial Ecology, T E Graedel and B R Allenby, Prentice Hall, Eaglewood Cliffs, 1995.

[5] Castings Technology International, The Foundry Mass Balance Project, 2003, pp 72.

[6] Department of the Environment, Energy Saving in Foundry Services, 1995, pp 45.

[7] Department of the Environment, Transport and the Regions, Non-ferrous Foundries Energy Consumption Guide 38 (2nd Edition), 1997, pp 30.

[8] Moore, C.M., Rohrig, K. and Deike, R. Foundry Trade Journal International, 1999, p.37-41.