A Modified Life Cycle Inventory of
Aluminium Die Casting

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August 2003

A thesis submitted for the degree of Master of Engineering of the Deakin University

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Declaration

This thesis contains no material which has been previously accepted for any other award of any other degree or diploma in any university, institute, or college, and contains no material previously published or written by another person, except where due reference is made.

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Acknowledgements

Without the assistance of many people this body of work would not have been possible. I would like to thank the following:

The Commonwealth Government sponsored Cooperative Research Centre for Cast Metals Manufacturing (CAST) for giving me the opportunity to do this research and contributing funds, knowledge and valuable time. This study would not have been possible without the assistance from CAST;

My supervisors, Dr. Eric Hu, Prof. Saeid Nahavandi and Dr. Linda Zou at Deakin University who have given me guidance and support;

The people at the plant where the study was performed, including machine operators, maintenance personnel, engineers, office staff and management for helping me to understand their process and giving the project a useful direction;

Dr. Rajah Tharumarajah and Dr. Paul Koltun at CSIRO for their help in assembling the GaBi3v2 software model and assistance with process parameters;

My family and friends who have supported me through the study;

Anna, my partner who has helped in so many ways which cannot be described.
Abstract

Aluminium die casting is a process used to transform molten aluminium material into automotive gearbox housings, wheels and electronic components, among many other uses. It is used because it is a very efficient method of achieving near net shape with the required mechanical properties. Life Cycle Assessment (LCA) is a technique used to determine the environmental impacts of a product or process. The Life Cycle Inventory (LCI) is the initial phase of an LCA and describes which emissions will occur and which raw materials are used during the life of a product or during a process. This study has improved the LCI technique by adding in manufacturing and other costs to the ISO standardised methods. Although this is not new, the novel application and allocation methods have been developed independently. The improved technique has then been applied to Aluminium High Pressure Die Casting. In applying the improved LCI to this process, the cost in monetary terms and environmental emissions have been determined for a particular component manufactured by this process. A model has been developed in association with an industry partner so this technique can be repeatedly applied and used in the prediction of costs and emissions. This has been tested with two different products. Following this, specialised LCA software modelling of the aluminium high pressure die casting process was conducted. The variations in the process have shown that each particular component will have different costs and emissions and it is not possible to generalise the process by modelling only one component. This study has concentrated on one process within die casting but the techniques developed can be used across any variations in the die casting process.
Thesis Outline

Chapter 1 – Introduction

This chapter will introduce the topic of “A Modified Life Cycle Inventory of Aluminium Die Casting” by providing background to the reasons why it was chosen. The industry of aluminium die casting is also briefly described. A short introduction to the techniques employed is also given together with what the study hopes to achieve.

Chapter 2 – Literature Review

The literature search was split into three major parts. This first part of the chapter deals with die casting, the associated processes and equipment and environmental issues related to it. Life Cycle Assessment (LCA) is covered in the second part of the chapter including work conducted into other processes and products. The last part of the literature review deals with the LCA software that was available.

Chapter 3 – Methodology of Study

This chapter describes the path of study from the initial gathering of the data through the creation and testing of the models. The study began with the traditional LCA methodology of the definition of the goal, scope, functional unit and system boundary of the study. Once defined, the collection of the data for the LCA study began with the creation of the cost-usage model to store all of the data for the Life-cycle Inventory (LCI). The results from this model were fed into the commercial GaBi3v2 software where another model was created for the high pressure die casting process. The cost-usage model was then further developed as it was deemed a more useful tool than the commercial software. From the cost-usage model and the GaBi3v2 model the results were collated.

Chapter 4 – Cost Usage Model Development

This chapter describes the development of the Cost-Usage (CU) model from the beginnings as a simple data storage and collection spreadsheet through to the final model which outputs the entire Life Cycle Inventory (LCI) of the aluminium high pressure die casting product. The further development of this model at the end of the study enables it to be a more useful tool for the process studied than the commercially available software. This chapter goes into the features of the model that could be of further interest in terms of continued study or industry application.
Chapter 5 – LCA by commercial Software

A commercial software package was purchased along with a database of information on materials. This chapter goes through the setting up of the model within the software, entering the results from the Cost-Usage model and other data which was gathered. The presentation of results from the model are shown at the end of the chapter.

Chapter 6 – Case Study

This chapter sets out the application of the Cost-Usage (CU) Model for two different aluminium components, both manufactured using the high pressure die casting process. The Casting AA and the Casting BB are both cast in the same plant using different sized die casting machines and different finishing processes. The data available for these components is actual data. The Casting AA is the only component to be modelled using the commercial GaBi3v2 software as the LCI output from the CU model demonstrates the points to be made more clearly. The chapter concludes with a comparison between the results for the two castings.

Chapter 7 – Discussion

The Discussion chapter follows through the points of the study that have eventuated from the previous chapters. The LCA tool is discussed in its methodologies and applicability to aluminium die casting. The Cost-Usage model developed with this study is discussed with the GaBi3v2 model including improvements which can be made to each. Data is discussed in length as it forms such a large part of this and any other LCA study. The value of the study is presented with the outputs and suggested improvements to the process. Further work is presented followed by the conclusion to the study.
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Chapter 1

Introduction

1.1 Outline of Chapter

This chapter will introduce the topic of “A Modified Life Cycle Inventory of Aluminium Die Casting” by providing background to the reasons why it was chosen. The industry of aluminium die casting is also briefly described. A short introduction to the techniques employed is given together with what the study hopes to achieve.

1.2 Background

Aluminium die casting is a manufacturing process used to form complex shapes from aluminium. Molten aluminium is fed into a die to solidify into intricate shapes which have a variety of uses from automotive engine blocks to mobile phone cases. 54 million kilograms of aluminium (Department of Industry Science and Resources 2000) is cast per year in Australia alone. Four million tonnes of aluminium is high pressure die cast each year world wide (Young and Eisen 2000). Increasing amounts of every automobile and electronic device are being die cast in aluminium and the industry is growing worldwide.

Whilst a lot is known and researched about the process itself, very little is known about the environmental consequences of the process. How much aluminium die casting contributes to greenhouse gases and global warming is a question that is increasingly becoming more important.

Life Cycle Assessment (LCA) is a technique which has become common in assessing the environmental impact a product or process has. By detailing all of the inputs to the product or process and all of the outputs and then assigning a value to them, a total value can be placed on the environmental impact of the process or product. This can then be used for comparison with another product or process. Doing this type of assessment, it can also be seen where improvements can be made to lessen the environmental impact.

The LCA methodology has gained wide acceptance and is commonly used up to the inventory stage. Assessing the impact of the inventory is very subjective and as such there is no agreement across various bodies as to how this part of the assessment should be standardised. This International Standards Organisation has addresses the issue in part with the ISO 14000 but does not fully deal with the problem, leaving issues such as weighting of results, out of the standards. The LCA methodology also does not address the cost of the process. It is aimed at the environmental aspect and can give a number to this but does not give a monetary value.

This project seeks to develop a new methodology and model which can be used primarily for the die casting industry and secondarily in other manufacturing areas. This
new methodology will use the Life Cycle Inventory (LCI) phase of the LCA methodology and modify it to include the manufacturing cost of the die casting process.

1.2.1 Current Die Casting

Die casting is a process that is driven by cost. Margins in the industry are commonly very low and reducing cost is seen by many die casting companies as the number one priority. Many of these die casters are also environmentally aware of the potential damage that is caused by their process. The problem is that no specific tools are available to determine and quantify the environmental load created from this commonly used process.

To gain wide acceptance from industry participants, environmental benefits must be linked to cost benefits. Either by a taxation system that penalises bad environmental practices or by the cost benefits of using less resources (energy, water, aluminium, et cetera.). Many companies have the desire to be good corporate citizens but it helps to give the environment priority if there is also a cost benefit.

Clean drinking water is possibly the most valuable substance on this planet. Currently in the area where this study was carried out, Victoria, there are water restrictions in place because the water reservoirs are at 40 percent of their capacity. The die casting process relies heavily on water for heat transfer and as a general process material. It is an aim of this study to determine how much water the process uses and where it is used. From this information, improvements to use less water and recycle more water are hoped to be gained.

As mentioned above, as an incentive for environmental improvement, energy costs are increasing. The current methods of generating energy in the area under study use up finite resources. As these become more scarce, the cost will be driven up by economic factors. Even as new, clean technologies are developed for electricity generation, the cost of these technologies is higher than the current methods.

The Victorian base load electricity is among the highest emitter of Greenhouse Gases (GHG) per megajoule (MJ) in the world. Add to this the emissions to air from the burning of natural gas to power furnaces, and it is clear that the emissions to air from this process are not going to be low. The questions are, what are these emissions? Where in the process are these emissions coming from? What improvements can be made to the process to improve and reduce the emissions to air? There is a link between the cost of energy and the emission of GHG, but it will be dependant on the types of energy used and at what efficiency. This study will move towards establishing this link.

1.3 Objective

The objective of this study was to use the Life Cycle Inventory technique to assess an aluminium product manufactured using the die casting process and to evaluate the
viability of this technique with regard to its use for this process. This work details the emissions to air, water and land from the process and also some of the more harmful impacts associated with it such as greenhouse gas, human toxicity and heavy metals emissions. Also, the process has been modelled in terms of the usage of materials and the cost to manufacture the component. From this work, a model which marries both the LCA technique and cost has been developed.

Specifically, this study is attempting to determine the cost of making a die cast component with the amounts and types of energy used, the amounts of resources depleted (water) and the emissions to the environment (air, land and water) from the process.

To continue this line of study to a full Life Cycle Assessment (LCA) requires the impact phase of the LCI to be analysed. This is part of the further work proposed.

1.4 Scope

To conduct a full ‘Cradle to Grave’ LCA study would require more resources than were available to this study and as such the scope of this study is to work within the die casting plant only and is not dealing with the raw materials involved, or the use of the product outside of the plant. Energy usage is included, specifically off-site emissions associated with the production of the energy. Other emissions generated off-site in the manufacture of the materials brought into the plant are not considered. Although these are considered very important, this work would comprise a separate study in itself.

The scope of this project is to work within the aluminium die casting industry. It is beyond the scope of this project to educate industry partners on how to use either the software or the models created. It is also not the intention of this project to work outside of the die casting industry. With further work, both the software and the subsequent model could be set up with to be used in other areas of industry.

Access to the plant under study was appreciatively provided and data was made accessible. The site was not however available for interruption to normal production and as such a lot of the data that was not able to be gathered was estimated as to conduct the testing required for exact results was not always possible. It has been shown in the study where this situation arose and which results have been estimated.

1.5 Aluminium Die Casting

Aluminium die casting is a manufacturing area which includes many different variations. High Pressure (HPDC), Low Pressure (LPDC) and Gravity Die Casting (GDC) are among the most common. It is a growing industry with over 4 million tonnes of aluminium being cast in HPDC alone worldwide and increasing amounts of steel and cast iron in an automobile being replaced by aluminium (Young and Eisen 2000).
Aluminium die casting is a very energy intensive process. Even if the original material is removed from the energy equation (as is the case with this study), vast amounts of energy are consumed in the remelting and holding of the aluminium. When post processes such as heat treatment are added to this, the use of natural gas and electricity is high. Ramsell (Ramsell 2000) suggests that the melting and holding practices in a lot of foundries is inefficient and that by improving this would greatly lower the greenhouse gas emissions from such foundries. There are a number of different die casting processes that can be used and were considered for this study.

The process itself has been studied by spending a large amount of time in a die casting plant. By doing this, it is seen that the knowledge gained is real and that the research is relevant to the die casting industry. By interviewing personnel and physically collecting much of the data, a greater appreciation of the process was gained.

### 1.5.1.1 High Pressure Die Casting Process

High Pressure Die Casting involves the injection of molten metal into a steel die under high pressure. Molten metal is poured into the shot sleeve by either a ladle or a dosing furnace. A piston moves within the shot sleeve and moves the molten metal up the gate of the die at a slow speed. When the metal reaches the gate of the die, the speed of the piston increases and the metal is injected through the gate and into the cavity at high velocity (> 20 m/s) and high pressure (up to 10 MPa). Due to the high pressures and velocities of the metal, the flow is atomised and fills the cavity in a spray type form. When the cavity is full the piston exerts an even higher intensification pressure to squeeze any air pockets (porosity) into the smallest possible size. The aluminium will then solidify into the shape of the cavity. The die is generally split into two halves and the machines are usually set up with the die between two platens (one fixed to the machine and one moving on slides). The moving platen will have half of the die attached to it and it will move back after the aluminium is solidified so as the part can be extracted from the die. The fixed half of the die will not move as it has the shot sleeve attached to it. After the component is extracted from the die, the cavity surface will be sprayed with a lubricant release agent to ensure the aluminium will not stick to the die when the part is ejected. The die will also be internally cooled with water to remove the heat from the process and it may also be internally heated using oil if a part of a die cannot maintain enough heat to keep a thermal balance across the die. The size of the machine to make a component is determined by the injection pressure of the metal and the area over which it is projected. A simple force - area calculation will determine how many tonnes of force is required to keep the die closed as the metal is injected into the die and intensified. Machines can be as small as 10 tonnes and as large as 4000 tonnes of locking force. The advantages of this manufacturing process are that it can produce a semi-finished component of high dimensional accuracy with a good surface finish in a short cycle time. Cycle times for this process vary from 10 seconds for small components manufactured in small machines to 200 seconds for large components made in large machines. The disadvantages of HPDC are the high capital cost of the dies and the casting machines. Typical components made using this process are automotive transmission cases and engine blocks. This process is also
used for the casting of other metals such as zinc, brass and magnesium with only minor modifications.

1.5.1.2 Low Pressure Die Casting

This manufacturing process uses a steel die which it located above a holding furnace of molten aluminium. The die is coated with a ceramic based die release coating, which is applied prior to service and lasts for up to 200 shots depending on conditions. The metal in the holding furnace is pressurised to 1 bar and the metal is forced up a riser tube and into the die. The metal flows into the die in a solid front and will fill the die from the bottom to the top. Because of the slow filling, solid front of the metal flow, turbulence in the flow is minimised and as such a high integrity casting with minimal porosity will be formed. The advantages of this casting process are that a high integrity casting can be made which can be heat treated in a later process and also more complex shapes which can include internal sand cores can be manufactured. The disadvantages of this manufacturing process are that the cycle time is relatively slow due to the die filling and solidification being slow. The die temperature is critical (cannot be too hot or too cold) and also the human operators for this process must be skilled for die preparation and also for subsequent inspection and finishing processes. This process is commonly used and represents approximately 10% of the production at the plant studied (as measured in tonnes per year). Components commonly manufactured using this manufacturing process include automotive cylinder heads and wheels.

1.5.1.3 Gravity Die Casting

This manufacturing process also uses a steel die into which the molten metal is poured either by a ladle or dosing furnace. The gravity process uses a similar die coating to the low pressure process. The die has the metal poured into a pouring chamber when it is in the horizontal position and the die is then rotated through 90 degrees into the vertical position. During this rotation the pouring chamber fills the die at a constant rate which results in a casting with similar properties to a low pressure die casting, due to the solid front fill with minimal turbulence. Alternately the metal can be poured directly into the cavity and the fill will be slightly more turbulent. Gravity die castings are also suitable for heat treatment. The advantages and disadvantages for this process are similar to those for low pressure die casting. Gravity die casting can be a very low capital process and as such is very popular with many other industries outside of automotive and electronic manufacturing. Brake callipers and engine intake manifolds are examples of components commonly made in gravity die casting.

1.5.1.4 Other Processes

Many variations of the above processes exist when the advantages of one process are coupled with another. One such process is Thixotropic (Semi-solid) Casting which is a variation on high pressure die casting where the metal is not molten when it is forced into the die. The metal is semi-solid and is forced into the cavity under high pressure. As the metal flows with a solid front, castings made using this process are of a high integrity and are suitable for heat treatment. The capital cost is slightly higher than that
of HPDC due to the metal handling requirements and the cycle time is comparable. Automatic transmission clutch pistons and suspension components are examples of components that can be made using this process.

1.6 Why High Pressure Die Casting?

The High Pressure Die Casting (HPDC) process is used across the globe and is recognised as a process which will continue to grow as the automobile makers in particular, strive to decrease the weight of their products. It is the drive to use lighter materials and the development of processes such as HPDC that are used in the manufacture of products from these lighter materials, that makes this type of study important. It is not easily recognised by the industries that use HPDC what affect the process has on the environment. It is also not clear to these industries what effect changes to the process could have on the environment. HPDC has also been chosen due to it being the major casting process used by the some of the major stakeholders in the CAST Cooperative Research Centre (CAST CRC). From this association it was also possible to gain access to a die casting plant whenever required and also the stakeholders provided data for the study.

1.7 Environment and HPDC

As a generalisation, die casting companies in Australia are not aware of the environmental impact of the processes that they use. The monetary cost may (or may not) be accurately known but at the time of writing it was very rare for any die casting company to have even explored the environmental cost of their business. Few have put in place environmental management systems (EMS) and even fewer have had them accredited to international standards (such as ISO 14001). Using the ISO standards for Life Cycle Inventory means that this study would sit one level above any organisation that has an EMS and would fit well in with a die casting company’s EMS.

One of the main reasons for this attitude within the die casting industry is a matter of cost. It can be expensive to set up an EMS and whilst it can be beneficial financially, this fact is not recognised by many organisations. This study attempts to link the ideas of cost and environment and show how one does affect the other and improving one will have a positive affect on the other.

On the aspect of cost, energy in Australia is too cheap and too readily available for industry to make substantial investments to conserve it. Water is also too cheap and even though it is a very precious resource which is rapidly running out, industry is not encouraged to minimise its use or maximise its re-use. These facts will change in the future as supply and demand dictate a rise in the cost of these resources but it is the organisations which act earlier that will reap the maximum benefits. When change is forced by increased cost the optimum solutions may not be able to implemented due to time and capital cost restraints.
The capital cost restraints prevent many organisations from doing more than they currently do because of the relatively small size of the Australian industry and the large amounts of capital required. When capital is available and the choice is between cheap equipment or energy efficient equipment (the two aspects rarely occur in the same piece of equipment), the payback periods are too long to choose the efficient equipment. This constraint will continue to plague the Australian industry until energy becomes more expensive (or more heavily taxed to pay for the damage).

1.8 Life Cycle Assessment

The first stage of any Life Cycle Assessment (LCA) is to define the goal and scope of the work. Then, SETAC (SETAC 1993) defines an LCA as being comprised of:

- Life Cycle Inventory
- Life Cycle Impact Analysis
- Life Cycle Improvement Analysis

Figure 1-1 shows how the first two components are linked and then move to the interpretation phase of the assessment. From the interpretation phase comes the improvement analysis. The Life Cycle Inventory (LCI) is the methodology of quantifying the inputs and outputs from the life cycle of a product or process. Life Cycle Impact Analysis is the qualitative and/or quantitative process to characterise and assess the effects of the environmental loadings identified in the inventory component. This phase
requires the use of a lot of data specific to the product or process. The Life Cycle Improvement Analysis is the development of the interpretation into specific improvements to the product or process with the aim of reducing the environmental load created from the product or process.

The life cycle of a product is usually divided into these three phases:

- **A Production phase** which includes the manufacture of the product and all of the materials used in the process including the base material. For example, the manufacture of die cast aluminium transmission case for later use in an automobile. Included in this phase would be the aluminium and all materials used to transform it from a bauxite ore to the finished die cast component.

- **The Usage phase** where the product is used for its intended purpose. To continue the previous example the transmission case will be manufactured into a transmission and assembled into an automobile. The automobile will be used for its life and the usage phase takes into account the emissions arising from its use and also includes resources depleted.

- **The Disposal phase** is the final stage of the product where the automotive transmission will not be of any further use and can be recycled or sent to landfill.

Added to these phases is the transport of all materials and the product during the different phases. This is often treated separately as another phase or can be incorporated into the existing.

Determining the environmental impact is a subjective process that is based on the use of resources, outputs to the environment and the damage of those outputs. Once this impact is determined, the study can be used to see what part of the product’s life cycle is having the largest impact and improvements to the product or the processes used in its manufacture can be targeted.

### 1.9 Total Cost Assessment

The LCA methodology does not address the cost of the process. It is aimed at the environmental aspect and can give a number to this, but does not give a monetary value. Introducing the concept of the cost into the Life Cycle Assessment could give the outcome of assigning a monetary value to the process and the environmental impact of the process. Norris (Norris 2001) suggests that all costs including potential costs associated with the future risk of current activities be included in this cost. A Total Cost Assessment (TCA) incorporates this idea into the LCA methodology. This study does not cover this detail but looks at incorporating the manufacturing cost into the LCA / LCI methodology.
1.10 Benefits of doing this work

At the beginning of this study it became evident that the process of die casting was a very wasteful process. Many resources were used and not very efficiently because there was no need to. As the business of making die castings is all about cost it was determined that the best way to educate the organisation was to put the benefits in the terms best understood, cost. By relating the environmental aspects back to a cost it becomes much easier to demonstrate a need for the improvement. When waste has a cost, the recycling cost can be offset. This project is all about relating the process of die casting to its environmental impacts by using cost.

Doing this work has enabled the exact amounts of all resources used in making a die casting to be known and from this, associated emissions. Both usage and emissions are known for each part of the process and through this, improvements have been targeted. As these are related to cost wherever possible, the improvements have been demonstrated to the plant management. This gives the improvements the best possible chance of being implemented and thus reducing the usage of materials and also emissions generated for the process of aluminium high pressure die casting.

1.11 Published Work

As part of this study a paper has been published.


This paper is shown in Appendix D.


2 Literature Search

2.1 Outline of Chapter

The literature search was split into three major parts. This first part of the chapter deals with die casting, the associated processes and equipment and environmental issues related to it. Life Cycle Assessment (LCA) is covered in the second part of the chapter including work conducted into other processes and products. The last part of the literature review deals with the LCA software that was available.

2.2 Die Casting

The literature in the area of die casting concentrates on equipment and process improvements. Environmental aspects of the process have been greatly ignored except to reduce the amounts of energy used in the process. Most of the literature in the area of die casting regarding process improvements was outside the scope of the study although any improvements in the process are still considered important.

2.2.1 Major Equipment and Process

This part of the literature is littered with improved equipment and processes for what was thought to be one of the major resource consumers and emitters of pollutants, the furnaces. No direct relations were found in the literature in the form of formulas or otherwise to give a quick fix to the problem of large amounts of energy being consumed to melt the metal. The literature searched concentrated on the natural gas furnaces since the electricity in the locality under study is not competitive on cost no matter how efficient the electrical furnace may be.

It was reported by Koch that furnace capacity should be kept close to the required melt rate for the plant for economy. This is because any furnace designed for melting will not be as efficient at holding the metal in the molten state for long periods of time. Koch also reported that preheated metal which is pushed into the molten metal increases the likelihood of oxide build-up (hard spots) in the molten metal which can then be transferred to the castings resulting in machinability problems at the machining part of the process (Koch 1989). Preheating the metal by using waste heat is thought to be a good way of improving the efficiency of the process.

Of the newer types of designs which are more efficient, Koch reported that a stack melter will have approximately 50% of the melting costs of a conventional reverb furnace, as is currently used in the plant under study. Also one operator is required for the entire stack melting process (for a 12,000 tonnes per year plant) compared to several operators for other systems (Koch 1989).
The other major type of efficient natural gas burning furnace, fitted with a specially designed regenerative burner will have <1.5% melt losses compared to 1-3% for a normal gas reverb furnace whilst being approximately twice as efficient (Guthrie and Link 1999).

The major melt loss from the furnaces is dross, which is formed from aluminium oxides when the molten aluminium reacts with oxygen. The major causes of dross that are controllable, are excess air through the doors or other openings, improper burner installation and improper air-gas adjustment (Gilstrap 1991), which all result in excessive oxygen being introduced into the furnace. Also, improper burner placement may impinge onto the metal or create turbulence on the metal surface, which will promote dross. Improper air-gas adjustment is by far the biggest cause of dross losses (Gilstrap 1991).

For best results to minimise dross losses inside the furnaces, there are no substitutes for good equipment and good melting practices when melting aluminium (AFS 1993). Preheating is important because it helps to eliminate absorbed and chemically combined gases and the moisture that is present on the ingot surface. It is important to avoid unreasonably high temperatures (< 760°C) and excessive holding times as this will lead to coarse-grained structure with low mechanical properties and increase the chances of gas absorption and dross formation (AFS 1993). Direct-fired reverberatory furnaces (where the flame is directly fired on to the metal) are likely to produce large quantities of dross and high rates of gas absorption if melting practices are not controlled carefully (AFS 1993).

Sloping dry-hearth reverberatory furnaces have the highest melt losses (2-12%). To minimise this, flame impingement should be minimised and design melt rates not exceeded. Excessive thermal temperatures in the melt zone will increase melt loss. Charging of light bulky scrap should be avoided in this type of furnace. (AFS 1993).

Stack/tower furnaces are high-volume, high-efficiency melters with low melt losses (2-3%) (AFS 1993) whilst the wet bath reverberatory furnace as used in the plant under study generally have melt losses of 3-5% (AFS 1993).

### 2.2.2 Environmental Issues

With regard to the emissions from the furnaces, the foreign matter from the furnaces exhaust flue is a mix of sulphur dioxides (SO₂), carbon monoxides (CO) and carbon dioxide (CO₂) together with oil fog and dusts from contaminated scrap material. The dust content increases at the time of dross removal and the level of emission is dependant upon the construction and method of furnace operation (Koch 1989).

A tower/stack melting furnace will generally not require extra dust removal or gas cleaning plant to be within European standards and the noise level of a stack/tower furnace will be below 80 dB (Koch 1989).
One of the emissions from the burning of natural gas is oxides of nitrogen (NO\textsubscript{x}). The factors affecting NO\textsubscript{x} emissions are:

- Combustion air temperature – the higher the combustion air temperature, the higher the efficiency of the combustion process but the higher the NO\textsubscript{x} emissions.

- Flame temperature and propagation speed – the higher the flame temperature and propagation speed the higher the NO\textsubscript{x} emission will be so to reduce this injecting an inert gas or products of combustion (POC) into the flame is common practice. POC need to be recirculated in the furnace.

- Air / Fuel ratio – to much excess air will create high NO\textsubscript{x} emissions but the more excess air the lower the CO emission. 10% excess air is recommended. Excess air can also be introduced through gaps in the doors et cetera. if a positive pressure inside the furnace is not maintained (Guthrie and Link 1999).

2.3 Life Cycle Assessment

2.3.1 LCA Overview

Life-cycle Analysis or Assessment is a technique which was first developed in the 1960’s but did not gain a wider acceptance until the 1970’s (Stone 1997). It has its primary use in determining the environmental damage caused by a product or process. LCA methodology is still being developed (Burgess and Brennan 2001) with a number of differing variations in existence. The most widely accepted is the Society of Environment Toxicology and Chemistry (SETAC) guidelines which were released in 1993. The literature has a definite skew toward the chemical industry and it is this industry which seems to use this process the most and in the most detail. Other industries use LCA as an experimental procedure while the chemical industry uses it as a matter of course in the design of new plants and chemicals. The SETAC guidelines are being replaced by the ISO 14000 series which involve ISO 14040 – 14043 detailing the full LCA process and a standard methodology which is slowly being followed in all studies. The difference between the SETAC and the ISO versions are in the interpretation phase with the ISO using more sensitivity and further analysis (Burgess and Brennan 2001).

LCA will comprise four main stages (SETAC 1993; Lupis 1999):

A goal definition and scoping stage – this should be clearly defined to ensure what is and is not to be included in the study.

An inventory stage – process flow charts are constructed to represent all flow into and out of the system, and materials balances are calculated to establish the net inputs and outputs. The life-cycle Inventory is often a long list of raw materials, energy and
releases to atmosphere, land and water. The definition and scope should clearly define to what depth the materials will be analysed.

The impact assessment stage evaluates environmental effects and comprises three steps. The first is a classification step in which the inputs and outputs are sorted according to the kind of environmental problems they may cause. In the second characterisation step, all inputs and outputs within a class are translated to a common measure, such as “carbon equivalent”. In the third valuation step, the various impact classes are weighted so that the Life-cycle assessment can be reduced to a single score. It is this step which causes the most controversy since it is subjective and as such, may give differing weightings according to which country it is in or how damaged the environment is already in that area.

The improvement or interpretation stage draws conclusions from inventory and the impact stages to give options for improving the environmental score of the product or process.

Through the literature the common point for argument is the impact assessment phase of the analysis (Lupis 1999). This view is common due to the fact that for each analysis completed, there will always be subjectivity whilst there are always differing ways of equating different parts of the inventory. There does not exist a common unit which all parts of the analysis can be compared.

2.3.2 LCA of Other Processes and Products

The review has found many examples where a LCA has been performed on products. Abrahamsson (Abrahamsson, Babazadeh et al. 1998) studied a LCA on silicon and gallium arsenide transistors, finding the LCA process was able to show that what appeared to be less environmentally friendly was actually better when looked at through the whole life cycle (the gallium arsenide). Sweatman (Sweatman and Simon 1996) conducted a LCA on an Electrolux vacuum cleaner with the objective of not only discovering the environmental impact of this product but also comparing LCA tools (software) for use in this analysis. It was found that the more expensive software (SimaPro 3.0) can be justified if an in depth study is required but the cheaper software (Eco-Indicator 95) is suitable where the designer is attempting to discover which material may be more environmentally friendly.

The area in which LCA studies are most prevalent is the chemical industry. This is evidenced by examples in the area of desulphurisation of gas oil (Burgess and Brennan 2001) and the work of the chemical industry in general which uses LCA as part of the operating environment. Other LCA studies found include a telephone, automobile materials and kerbside waste recycling. No literature has been found relating LCA to die casting or any other forms of casting. This area of the study of LCA has not been previously reported in the literature if it has been attempted before.
2.4 Software

To do a Life Cycle Assessment (LCA) of a process requires a lot of data to be collected in the inventory phase and to be analysed in the impact phase. To do this a software package is commonly used. Since the objective of the project was to study the aluminium die casting process in detail, when looking at the different software available, it was always going to be important to find a package which could effectively work with this process. The search for suitable software and associated literature included the following criteria: compatibility with known databases; work with other projects within the CAST CRC; literature and demo versions of the software were available; and word of mouth – interviews with LCA practitioners.

Three LCA software packages were reviewed by obtaining demonstration versions and attempting to use these in the limited way afforded by these scaled down and ‘light’ versions of the full scale software. All of these versions did not have all features of the commercial software. The tested software was SimaPro, LCAiT and GaBi3v2. Some of the main features looked for in each software were the databases which come with the software, ease of application and usefulness of the outputs of the software. Not all of these were able to be assessed in each software for reasons which will be outlined.

2.4.1.1 SimaPro

SimaPro (Pré Consultants B.V. 2001) has been developed by Pré Consultants B.V. in the Netherlands. This software is widely recognised in much of the literature and has been reported by de Caluwe (de Caluwe 1997) to be the best value of the software reviewed (although the versions reviewed by de Caluwe were previous versions of all of these softwares and databases). SimaPro came with a complete set of manuals so it was easy to discover how to broadly use the software. It also has a demonstration program which is effective in showing all of the features of the software. A full ‘Help’ file was also available. This software proved easy to use although modelling of a process (rather than a product) did require extra work.

The database which comes with the package is quite extensive and reputed to be one of the best available. By doing a quick analysis it was found to be deficient in most areas of die casting and this is not expected to improve with a larger analysis. Extra data can be imported into the software from outside sources in the SPOLD (Society for Promotion of Life-cycle Assessment Development) format, although this software is not yet compatible with the SPINE (Chalmers University, Göteborg, Sweden) format used with some other software.

This software also comes with a macro type programming called ‘Scripts’. This enables the user to put extra functions in the software and could be useful for later additions. The scripts could not be tested as it is only available with the commercial version of the software.
The current price for the educational version is EUR 1200 and a further EUR 500 for the Franklin Database (this may not be required and can be purchased at a later date). This equates to approximately AUD$2,050.

2.4.1.2 LCAiT

LCA Inventory Tool (Industriteknik 1999) is a software tool produced by Chalmers Industriteknik in Göteborg, Sweden. This software came with a partially complete manual so it was difficult to see how it works. From what could be seen, its framework seems to be similar to SimaPro but all of the features of the software are not known. The database is of reasonable size and data can be imported and exported using the SPINE format. The software in the ‘Light’ version did not come with a help file or any other ways of properly discovering how to use it properly. The price of this software is unknown but is thought to be more expensive than SimaPro from indications given and word of mouth.

2.4.1.3 GaBi3v2

The GaBi3v2 3 Software System for Life Cycle Engineering (Institute for Polymer Testing and Polymer Science (IKP) 2001) has been developed by the Institute for Polymer Testing and Polymer Science (IKP) at the University of Stuttgart in co-operation with PE Europe GmbH (PE), Dettingen/Teck. It proved difficult to use and did not come with any manuals and only a limited help file. This software comes with recommendations from CSIRO (who have a commercial version) and it was believed to be good for modelling processes. The price of this software was AUD$3200 for the basic version and the full commercial version costs AUD$12,000 with the full database.

As this study is going to work closely with the CSIRO study being conducted with the CAST CRC, the recommendation of this software was highly regarded.

2.4.1.4 Software Conclusions

All of the software packages did not seem to have any type of database which would be suitable for die casting and in the ‘light’ or demonstration versions they all had large drawbacks. Word of mouth and the availability of local support and training brought the decision down to SimaPro and GaBi3v2. The decision to purchase the GaBi3v2 software came from the recommendation of the CSIRO and the accessibility to their help with problems.

2.5 Literature Summary

The available information which has been reviewed as part of this project suggests that the area of Life-cycle Analysis or Assessment is a maturing area of study in which a lot of work is being done. There is always the subjectivity of the impact assessment phase of the LCA, which at this time is the issue which has the least agreement among all of the literature reviewed. LCA is normally conducted on a product and is not widely
conducted on a process. The LCA has not been reported as being conducted previously in the area of die casting (any type or material) although the analysis has been conducted on other processes in the past. This is true for the chemical industry in general where it is widely used.

Life Cycle Assessment on die casting is an area where there appears to be no reported study conducted. The impact assessment area of the LCA is a subjective area where agreement is difficult to find among the differing methodologies. To tailor the LCA methodology to aluminium die casting and providing a total cost to this process in the form of equating all of the differing areas of the LCA is an area of study which has not been reported.
3     Methodology of study

3.1 Outline of Chapter

This chapter describes the path of study from the initial gathering of the data through the creation and testing of the models. The study began with the traditional LCA methodology of the definition of the goal, scope, functional unit and system boundary of the study. Once defined, the collection of the data for the LCA study began with the creation of the cost-usage model to store all of the data for the Life-cycle Inventory (LCI). The results from this model were fed into the commercial GaBi3v2 software where another model was created for the high pressure die casting process. The cost-usage model was then further developed as it was deemed a more useful tool than the commercial software. From the cost-usage model and the GaBi3v2 model the results were collated.

3.2 Introduction

The methodology behind the study was to follow the ISO 14040 Life Cycle Assessment group of standards and to deviate in the area of cost. As the beginning of the study was conducted whilst based in the plant, information was readily accessible although not always in a usable form. It was decided that because the information for cost for the plant was available, it was collected and stored with the usage information although the cost information was confidential and could not be published. The cost-usage model was developed to hold the data and output the details for the Life Cycle Inventory (LCI). As this information was input to the commercially available GaBi3v2 software the cost-usage model was further developed to be more useful and easier to use. The GaBi3v2 software was found to be difficult to use and by the conclusion of the study the cost-usage model had been developed to give more than just a LCI and can be used to pinpoint high cost, waste and emissions in the process and areas for improvement.

3.3 LCA Methodology

3.3.1 Goal and Scope

The goal of this study was to determine the environmental impacts of Aluminium High Pressure Die Casting as a process. To do this a single casting of product was evaluated as well as the process itself. The process was only considered from gate to gate, i.e. materials into the plant and everything which leaves the plant either as solid and liquid waste, emissions, recyclable material and die cast product. Major tonnage of raw material was also required to be considered as part of this study, for example, natural gas, electricity, aluminium, water and die lubricant. The manufacture of the
thousands of consumables used in the plant was not considered. Transportation of raw materials and capital equipment will also not considered for this study.

3.3.2 Functional unit

One kilogram (kg) of aluminium casting as shipped to the customer. When die casters talk of delivered product, tonnes of delivered product is more commonly used but when the die casting being modelled may (and in this case does) weigh less than one kilogram it was decided that it was easier to relate the results when they are measured in kilograms rather than tonnes.

3.3.3 System boundary

The system boundary for this study is the boundary fence of the plant. Transport of materials to the plant and transport of waste products has not been included. Capital equipment has not been included but maintenance on this equipment has been included. Buildings and grounds have not been included. Due to lack of reliable data on the aluminium material (secondary aluminium ADC12) the system boundary has not been extended to include the aluminium supplier.

![Diagram](image)

*Figure 3-1: System boundary of study*

The system boundary includes off site emissions from the energy sources for natural gas, electricity and liquefied petroleum gas (LPG). Waste water emissions have also
been included for the industrial waste but not for sewage as no accurate flow could be obtained.

3.4 Process Plan

3.4.1 Visual

The first phase of estimating the process was to draw a flow chart of the process including all of the main operations (melting, casting, et cetera.) and assisting operations (compressed air, cooling water, et cetera.). This flow chart included as many inputs and outputs for the processes as could be easily identified and became extremely complex, but formed a solid base from which a more comprehensive list could be produced. The flow chart developed through the study is shown as an example in Appendix C.

Once created, the flow chart was only used for reference, as it was too cumbersome to work with as an on-going tool. However, the process to create the flow chart and the flow chart itself gave a clear understanding of the high pressure die casting manufacturing process. The information from the flow chart was then extracted into a simplified table form to show the key inputs and outputs of the process.

3.4.2 Table – Input / Output

The input – output table was created to hold the key information gained from the flow chart. The table was divided into Main Processes and Sub Processes. The main processes were considered those directly involved with the making of all high pressure die castings: Ingot (or Molten Metal Delivery); Melting and Holding; Filtering, Cleaning and Transfer; Holding at Machine; Casting; Finishing; Packing. The Sub-processes were considered to be those that assisted the Main processes: Transport; Forklift; Cooling Water; Compressed Air; Die; Holding Furnace; Waste Water; Machine Maintenance; Die Maintenance; Finished Processes; Labour; Services; Plant.

The table held the information on suppliers, type of information and data available, where an input went once used and any following processes. This table was useful to store information but proved to difficult to work with as a day-to-day tool. Once the information was collected and placed in the table, it was transferred to a spreadsheet that was used as the working document. This spreadsheet formed the basis of the Cost-Usage Model. From this point it became clear what usage data was required for the study.
### Main Process

<table>
<thead>
<tr>
<th>Melting and Holding</th>
<th>Inputs</th>
<th>Chemical Name</th>
<th>Supplier Name</th>
<th>Outputs</th>
<th>Output to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forklift</td>
<td></td>
<td></td>
<td></td>
<td>Forklift</td>
<td></td>
</tr>
<tr>
<td>Aluminium Ingots</td>
<td>ADC12</td>
<td>Aluminium</td>
<td></td>
<td>Molten Aluminium - dirty</td>
<td>Filtering / Cleaning</td>
</tr>
<tr>
<td>Scrap</td>
<td></td>
<td>Dross</td>
<td></td>
<td>Recycle</td>
<td></td>
</tr>
<tr>
<td>Ross cone</td>
<td></td>
<td>Waste Ross Cone</td>
<td></td>
<td>Solid waste</td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>Liquid Nitrogen</td>
<td>Air Liquide</td>
<td>Waste Nitrogen</td>
<td>Atmosphere</td>
<td></td>
</tr>
<tr>
<td>Flux</td>
<td>Aluxal 100</td>
<td>Pyrotek Pty Ltd</td>
<td>Combustion Gases (Flux)</td>
<td>Atmosphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Combustion Gases (Dross)</td>
<td>Atmosphere</td>
<td></td>
</tr>
<tr>
<td>Ceramic Furnace Brick / Refractory</td>
<td>Waste Ceramic Furnace Brick / Refractory</td>
<td>Solid waste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramic Tapping Block and Ring</td>
<td>Waste Ceramic Tapping Block and Ring</td>
<td>Solid waste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouples</td>
<td></td>
<td>Waste Thermocouples</td>
<td>Solid Waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouple Sheath</td>
<td></td>
<td>Waste Thermocouple Sheath</td>
<td>Solid Waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>CitiPower</td>
<td>Waste Heat</td>
<td>Atmosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Pulse</td>
<td>Combustion gases (Natural Gas)</td>
<td>Atmosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labour</td>
<td></td>
<td>Carborundum</td>
<td>Solid waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine Maintenance</td>
<td></td>
<td>Machine Maintenance</td>
<td>Atmosphere</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3-1 : Example of input – output table**

### 3.5 Data Collection

High pressure die casting is a complex process that involves over 200 known process variables. It was decided that the best way to discover all of the intricacies of the process was to spend time in the plant with the engineers, operators, maintenance personnel and the management team. Doing this ensured that all of inputs and outputs for the process could be accurately captured and it also established a relationship with the people in the plant. It was important that they understood what the study was about and did not feel threatened by it. This is essential because without the support of these people the study could not have been successful.
3.5.1 Data Collection – Stores

The purchasing department at the plant captures the usage of all materials that enter the plant. Although it is not in any way activity based, it is a way of determining all of the materials that are used in the plant and exactly how much of each are consumed for the 12 month period studied.

The stores at the site are managed using two linked computer software packages, an accounting management package and a proprietary bar coding software. The accounting management package is used to place all the orders, to monitor stock levels and to generate invoices. The bar coding software is used to capture usage from the storeroom via a bar coding system. Although the two systems are linked, they do not share common store numbers or names. Thus a cross referencing file was set up with the major items being manually cross referenced to determine the correct amounts used for the twelve month period. Of the thousands of items listed in the store, only 10 percent of these were considered of high enough usage or value to be considered in the study. However, particular items were included if their input into the process was known. Difficulties encountered included naming issues (two different names for the same material), changes in suppliers and different sizes of materials. Talking to the purchasing manager and the stores personnel solved all of these problems.

Two die casting processes are used at the site, the high pressure and the low pressure casting processes. Allocations based on a per kilogram of aluminium basis have been made as a lot of the plant data is not concerned with the high pressure die casting process selected.

In this study, the information about the cost of each item and exactly how much was used for the process was gathered for the calendar year 2001. The cost information is confidential and will not be published although it was used to verify the study.

For all chemicals and hazardous substances kept on site there is a Material Safety Data Sheet (MSDS) kept on site. This is required by law for this plant. On the MSDS, information such as the manufacturing company, major ingredients and any safety related information is kept. The information on the ingredients was very general and as such letters were written to major suppliers for more information. This yielded no results except for the aluminium supplier and as such the general ingredients were all that could be gained. This information was all placed into a spreadsheet.

3.5.2 Usage Data and Models

Data for electricity, natural gas, LPG and water usage was captured by talking to the Finance Manager and the rest of the accounting group. This data is metered by outside organisations and is billed directly to the company thus bypassing the purchasing department. The accounting department collect all electricity, natural gas and water usage and the normal allocation practice was made on a per kilogram of aluminium
shipped basis. Other information such as major repairs to capital equipment was also collected at this point.

The site collects records manually for the outputs from the plant to the metal supplier for aluminium dross, swarf and scrap steel. The manual records were then placed into spreadsheet for the study. Added to this were the records for the in-plant remelt of scrap. This was also not automatically collated by the plant personnel but was manually entered into the spreadsheet also for the calendar year 2001.

Natural gas is used to fuel the melting and holding furnaces and also for the holding furnaces at the casting machines. The melting and holding furnaces have meters on them and data was gathered from all of these furnaces over a two week period including a period of plant shutdown (4 day long weekend). From this, modelling was conducted of the furnaces and the actual gas use under different conditions such as melting and holding of molten metal. This was considered important as it was thought by the plant personnel that these furnaces were the highest gas users in the plant. A meter was also fitted to one holding furnace at the die casting machine and monitored for one week. This gave an accurate reflection on all operating conditions so this could also be added to the model. These models were used to reflect the use of all natural gas in the plant.

The largest users of electricity in the plant were known to be the heat treatment facility, cooling water system and the air compressors. Usage data from all of these was gathered and another model created to estimate the usage under different operating conditions. This model was extensively tested and led to improvements in the plant process that have been implemented since the beginning of the study. These include an air compressor management system that has significantly reduced electricity usage in this area and a modification of the quench tanks in the heat treatment facility, which has halved the electricity consumption of this part of the process.

Electrical meters were placed on required equipment in the plant to determine exact energy usage. Where this was not possible, estimates were used based on equipment ratings, motor sizes, burner sizes and old data.

Other data involving plant operations was also collected such as the capacity of scrap bins and the life of holding furnace crucibles. This data was estimated from the available store data and clarified from interviews with plant personnel.

3.5.3 Data Validation

Once all data was collected, it was all checked by talking to the people who use the materials. Where discrepancies were found they were investigated to discover why and what the correct value should be. This uncovered some discrepancies in the process between what was said to happen and what actually happens. An example of this is the fluxing of the melt furnaces. The furnace operators flux two furnaces daily using one type of flux. Using 10 kilograms of flux that is metered using a machine, the usage for
the year was considerably less than the calculated usage of 2 furnaces multiplied by 220 production days. In cases such as this the actual data was recorded.

In some cases the data was averaged over a period of time (such as 24 hours rather than on a piece by piece basis) because of differences in the way a process was conducted by different operators or at different times of the day.

3.6 Development of Cost-Usage (CU) Model

From the flow chart and the input – output table, headings were put into a spreadsheet to hold all of the information. At this time all of the individual spreadsheets which had been developed were all brought together so as all of the information was held in the one place. This made transporting and duplication of the data easier. A die cast product was chosen at this point to gather all of the data for and the model was built around this casting component. At all times whilst building the model, it was always intended that it could be used for any component manufactured by the same process.

For each input into the process, the quantity used of the material to manufacture the chosen die casting was entered into the model together with the cost of this input. The model calculated associated outputs according to the functional unit (per kilogram of casting shipped) and also the individual component usage and cost.

For example, based on the amount of aluminium used to make the part (shot weight) and the actual weight of the die casting (shipped weight), the scrap amounts were calculated plus all associated metal losses (dross, oily scrap) and labour amounts associated with the handling of this quantity of metal. These usages all had corresponding costs associated with them, as a result, as well as the usage amounts required the model would also output the cost.

By cross referencing to the other sheets in the model, the data used could be easily accessed and changed. As the information was fed into the model any anomalies in the results were checked and the calculations monitored and de-bugged. The plant personnel also used the model in a limited way in an attempt to find any problems and to make the model a more useful tool in the longer term.

In the development of the model a number of new and different ways of calculation losses were developed. The usual way of determining dross losses associated with a die casting is to take the dross losses for the plant and divide them equally according to the shipped weight of the component. It was noted by the author that the majority of the dross (approximately 80 percent) came from the remelting of the scrap in the wet bath reverberatory furnace. This is because the scrap is predisposed to being covered with lubricants from the casting process and when dumped into a molten bath of aluminium all of this burns off, often contaminating the metal. During the fluxing of the metal in the furnace, the flux reacts with these contaminates and brings them to the top of the bath. When all of these contaminates are raked off with a forklift a lot of metal also is raked off into the dross bin. Although some of the metal is recovered, a lot is not and is sent
to the secondary aluminium smelter for reprocessing which is a direct loss to the plant. Also, when the scrap furnace is raked compared to the molten metal holding furnace, the dross is of a different consistency and volume. Some measurements were made and the 80 percent number was decided upon after consultation with the plant management. This is a variable in the CU model that can be changed.

The yield of the casting (the shipped weight divided by the shot weight, expressed as a percentage) will determine how much dross is lost to the process. The lower the yield, the more scrap that must be remelted. As the melting of the scrap creates the dross, the dross loss is allocated by how much scrap must be remelted when making a casting and not the usual practice of attributing it based on the shipped weight alone. A lot of other waste and cost is attributed to the yield of the casting in the same way because significant amounts of energy are used to remelt the scrap aluminium.

The plant functioned with molten metal and ingot being delivered to the plant and scrap being remelted in the plant. It becomes difficult to determine where the original metal to make a casting has come from – the holding furnace or the scrap melting furnace? Energy was allocated as the original metal comes from the holding furnace or the ingot (melted) and the energy from the remelting of the scrap is also allocated to return the metal to the original molten state.

With so many variables in the high pressure die casting process it was inevitable that a lot of these variables would need to be included in the model to get a high degree of accuracy. Over 200 items are required to be put into the model. These range from the casting weight to the weight of the waste refractory when the furnaces are relined and almost everything in between. Further details of the types of inputs into the model and the calculations can be found by looking at Chapter 4 and at the CU model itself (Appendix C).

3.7 CU Model Validation

Once all of the data was collected and placed into the CU model, the results could be analysed for gaps and anomalies. As the gaps and anomalies were found the input data and calculations were checked and if a suitable explanation could not be found the plant was visited again to discover the reason behind the data. This process continued for the life of the study.

3.8 Development of Commercial Software Model

After a thorough search of the available LCA softwares, the GaBi3v2 software was chosen for this study. This was primarily because of the choice of CSIRO to purchase the same software and the large database that can be purchased as an option. As the CSIRO project and this study were linked under the CAST affiliation, this seemed the sensible thing to do since much of the data was common between the two projects.
Chapter 3
Methodology of Study

The purposes of using the GaBi3v2 software were to collate the LCI data from the CU model and determine the effect of the LCI that had been collected. As the GaBi3v2 software had a large database it was hoped that the Life Cycle Assessment (LCA) would be completed using this database. The software was also a good format for storing all of the collected data with a visual presentation. The CU model did not have the visual aspect and it was not within the scope of this study to develop it.

3.8.1.1 Building the Plant System

To use the GaBi3v2 software the first action was the creation of the process flow chart which outlines the major and minor parts of the process. This was created in the software from earlier work and parts of the process were changed and approximated in the model to relieve some of the complexity that was not easily handled by the software.

Once the process was laid out in the model, all of the information from the Cost-Usage model was placed into the framework. This required some changing of the CU model to get information into the right form, as the GaBi3v2 model does not work only with the functional unit (per kilogram of aluminium casting shipped) but has individual units depending on which part of the process is being considered. The output of one part of the process was required to match the input of the next. This caused a lot of problems in getting the model to produce an overall result.

The aim of this part of the study was to transfer the process and results from the CU model into the GaBi3v2 Software. The software did not allow this to happen easily for the most part and some parts of the process could not be transferred and as such were approximated. For example the finishing processes were incorporated into the casting machine (except for the heat treatment).

3.8.1.2 Localised Data

Life Cycle data needs to be specific to the area under study. For example, electricity data for most areas of the world will differ from the Victorian electricity grid where the base load power is provided by brown coal fired power stations. The data provided in the GaBi3v2 database was mainly European and as such not relevant to this study. Being aggregated data, it became clear that modifying this data would be difficult and as such alternative sources for relevant data were sought.

A very good source for disaggregated and reliable data was found from RMIT Centre for Design where electricity, natural gas and LPG data has been placed in the public domain. Unfortunately this data was in SimaPro format that cannot be transferred to the GaBi3v2 format and was placed in the database manually.

3.8.1.3 Development of the GaBi3v2 Model

All of the information from the Cost-Usage model was placed into the GaBi3v2 model and at this time it was becoming evident that the GaBi3v2 model lacked enough data to properly fulfil the requirement of a Life Cycle Assessment of the aluminium die casting
process. Most of the chemicals used in the process were not in the database and manufacturers of the chemicals were not forthcoming with information about them. In most cases, exact compositions were not able to be determined without proper analysis and this was beyond the resources available to this project. To do the LCA properly would require this or more helpful chemical suppliers.

3.8.1.4 Mass Balances

To check the accuracy of the model (preliminarily), mass balances were carried out to make sure all the mass / materials involved could be properly accounted for. This became more significant as the system involved a lot of waste and losses of important resources such as energy and water.

Calculating pollutant emissions using a mass balance is not straightforward as there are many variables that remain unknown to this study. It is not the purpose of this study to detail all of the complex chemical reactions that take place in the burning of fossil fuels in the furnaces and other equipment. These techniques were used solely to check the accuracy of the data obtained and to make approximations where no data existed.

3.8.1.5 Energy Balances

To correlate with the mass balances, energy balances were also carried out to properly determine where all of the energy was going and where it was leaving the system. The molten metal loses all of its energy as it solidifies back to a solid state and eventually back to room temperature. It was important to recognise where this energy was being lost so as future energy recovery improvements could be targeted. As a lot of energy is consumed in the process (outside of the molten metal) is was also important to get an exact idea of where general energy improvement could be targeted and by balancing the energy in each system this became clearer.

3.8.1.6 GaBi3v2 Model Conclusion

The GaBi3v2 software was a very complex piece of software and the model of the high pressure die casting process was also intricate. For all of this complexity, the results that came out of the software are not of high accuracy because of the quality of the data available in the purchased database and the known variations in the data obtained from the process itself. It was decided that to increase the quality of the data would be very time consuming and not within the scope of this study. Instead, it was determined to extend the CU model to generate the results required in a more general and useful format.

3.9 Further Development of the CU Model

The results at this time might indicate that the process had so many variables that one product would give very different results to another product made by the same process
at the same site/plant. To test this hypothesis and develop the model for more genetic use, a second product was modelled with the Cost-Usage model.

The second product was very different from the first and enabled many of the suspect variables to be changed such as the yield of the casting. Further development of the Cost-Usage model occurred whilst modelling the second component as a number of features were added to the to make comparisons between two components easier. Items such as amounts of energy used were further detailed and some of the emissions associated with the energy use were added to the model because energy is the main contributor to GHG emission from the process. This was easier to see from the Cost-Usage model than from the GaBi3v2 model.
4 Cost-Usage Model Development

4.1 Outline of Chapter

This chapter describes the development of the Cost-Usage (CU) model from the beginnings as a simple data storage and collection spreadsheet through to the final model which outputs the entire Life Cycle Inventory (LCI) of the aluminium high pressure die casting product. The further development of this model at the end of the study enables it to be a more useful tool for the process studied than the commercially available software. This chapter goes into the features of the model that could be of further interest in terms of continued study or industry application.

4.2 Overview of Cost-Usage Model

This model has been developed firstly as a working tool and secondly as something which may be used as a stand alone tool with a user friendly interface. The model is spreadsheet based to run in Microsoft® Excel 2000 software. It has been written without any macro programs and is based on formula manipulation of entered data.

The first sheet of the model is a questions page. This sheet is used to enter all of the necessary data for the model and would be the front end of the model if it were developed further. The questions are presented and the answers are placed into a cell. There are no safeguards against bad answers to the questions such as numbers that are unreasonable or impossible. Further work in this area could write protection against improbable answers.

The second page is a results page that details all of the major results that may be useful to management working in a die casting facility. This has cost to manufacture broken down into the smallest detail and also pie charts of these results. This page also gives information on energy consumption and GHG emissions from this energy consumption.

The Cost and Use sheet of the model contains all of the calculations and uses the information entered on the first page. Numbers in blue on this page should not be changed as they come from the first sheet of the model and should be changed there. Manipulation of anything on this page will change the model. All of the formulas on this page have been developed during the study. There are hundreds of formulas and these have not been detailed in this thesis although a list of formulas is available in Appendix A.

The next page of the model is an aggregated life cycle inventory that gives the materials used in the process as inputs in the commercial software. This is essentially a summary of the environmental results and also has some other calculations that have
been used in sensitivity analysis. This page is a work in progress and is not complete but has been left in the CU model as a future direction.

The CU model as published does not contain any of the confidential information gained from the plant during this study at the wishes of plant management of the site under study. This chapter mentions this data as it was used as the basis of the model but has since been given back to the plant and this part of the model is not required past the validation work that has been completed.

### 4.3 Data Collection Sheet

The data that was available from the site came in three different files. One file matched all of the materials in the plant to their numbers in the account control system together with a price and a description. The second file matched all of the materials in the plant stores to a description of the material and the store number and the account control system number. The third file was the actual usage information for the 12 month period under study and was the accounting system number, the quantity of materials and the total value of these materials but no description of the material.

With over 4000 different materials used in the plant the spreadsheet was set up to cross reference these three files to get a description of the material, the usage of the material for the 12 months, the price of the material and the total cost of the material for the 12 months. This information was not generally available and the way the information is collected in the plant is on a material by material process of getting one material out of the system at a time. This part of the sheet cannot be published but has gained the author a valuable insight into the real cost of running a die casting plant. This information would not have been surrendered for the study if it was going to be published and the author is grateful to the plant management for making this information available.

This information was then referenced in the model via the calculations. The calculations for cost and usage are taking information directly from this part of the spreadsheet. This works for the plant under study and there is no reason that this sheet cannot be replaced with the information from any plant in further use of this model.

### 4.4 CU Model Usage Calculations

The thinking behind the calculations for the material usage in different areas of the CU model is explained in the following section. A more complete list of the formulae can be found in Appendix A.

#### 4.4.1.1 Plant Operations

Data for uptime, hours of plant operation, machine cycle time and production days for the year are used to calculate the number of castings to be manufactured each shift
and per 24 hour period. This information is used throughout the model as a base for many calculations where data was averaged over a shift or a day or week.

### 4.4.1.2 Metal Use

The metal use equations are based on the use of aluminium for the plant (both ingot and delivered molten metal) and the scrap aluminium taken from the plant in the form of dross, swarf and oily scrap. This gives a gross and net amount of aluminium used in the plant for the 12 months. This method has inaccuracies as it does not account for the moisture content of the swarf, the non-metallic particles in the dross or the oil content of the oily scrap but was considered reasonably accurate as some aluminium is lost in the plant and this is thought to closely balance the equation.

An alternative method is to use the production of all of the components manufactured in the plant for the 12 months and multiply by the theoretical shipped weight. This method had large inaccuracies and was not used since it created approximately 20 percent more aluminium than was purchased for the 12 month period when a sample calculation was performed by plant personnel.

### 4.4.1.3 Labour PPE

The personal protective equipment (PPE) as used by machine operators was accounted for in the labour area on a per minute basis as labour is allocated to the process on a per minute basis. As such the cotton gloves, rubber gloves, earplugs and overalls are included in the labour component of every casting. This calculation then finishes with the cotton and rubber as per the functional unit from a later calculation for the amount of labour used in each component.

### 4.4.1.4 Casting Details

From the details for shipped weight and the weight of the biscuit, runner and overflows, the yield of the casting is calculated. One of the large variables in this area is the biscuit weight since the metering accuracy of the ladle is at best plus or minus 5 percent but quite often worse. This variable is built into the model for sensitivity to see how much this affects the overall results. Also built in is the actual weight of the casting compared to the theoretical weight of the casting. This can quite often be more due to the die flashing and the component having a thicker wall section than normal. Modifications to the die may also result in the casting being lighter than theoretical, consequently saving the company metal.

Also to be taken into account for all calculations is the reject rate of the casting which is the number of reject castings (including warm up castings) made divided by the total number of castings manufactured. This has implication throughout the model since every reject needs to be made again and also metal losses are compounded when the reject casting is remelted.
From this information the calculation of how much metal is required to make each casting can be made when losses are taken into account. The output also includes how much dross and oily scrap is lost per casting and then per functional unit.

4.4.1.5 Labour Use

All of the operations in the plant were modelled here for their labour content. This included the casting operator’s supervision, the casting operator, furnace operators, quality personnel, validation personnel, maintenance (die and machine) personnel and finishing operators. Each aspect was considered for the amount of time required to manufacture one casting, the output being in minutes per casting. When this is divided by the casting’s shipped weight, the output is in the functional unit of the study being per kilogram of shipped casting.

4.4.1.6 Capital

The capital that is considered for this study is that which is amortised into the piece price of each part, being the die bolster and inserts. The weight of these components and their expected life, give the amount of scrap steel produced per casting and functional unit.

4.4.1.7 Lubricants

The lubricants area of the model is where a lot of the waste and water usage was thought to be found and as such all of the variables were required to be captured. The die lubricant which is sprayed on to the die surface is mixed with water prior to application. The number of nozzles spraying the die and their flow rate are taken into account along with the spray time. This is also repeated for any water that is sprayed on to the die before the lubricant to cool the die surface. This gives a total amount of water which is sprayed on to the die as well as the amount of die lubricant used. The die lubricant is further broken down into its components according to the information from the MSDS collected earlier.

The tip lubricant is usually metered in measured amounts per shot and this is calculated to each casting and also the functional unit.

The warm-up release agent is used when the die is cold because at these temperatures the regular die lubricant will not work. It is applied manually and the amounts applied will depend on the operator applying it. Also the frequency of application will vary according to how reliably the die and the casting machine are running as the more often the machine stops the more warm-up lubricant is required. For this reason, the amount of warm-up lubricant is simply a division of the amount used for the plant for the year divided by the total aluminium used for the year. The amount is small so this inaccuracy is not seen as a major problem.
4.4.1.8 Machine Shot End Consumables

The machine shot end consumables are the copper plunger tip, the shot sleeve, the and the sprue bush and post which are at the end of the shot sleeve and are part of the die itself. These are consumed at different rates in the process.

The shot sleeve can be reconditioned a number of times before it is scrapped as can the plunger tip. These are recorded in the model and accounted for as such. The sprue post and bush are scrapped after use and are generally not reconditioned although they can be transferred to another die. These are all output as their weight of scrap material per casting and per functional unit.

4.4.1.9 Forklifts

The forklifts in the plant are leased by the organisation and include service contracts. Data was unavailable for service of these machines but the data that could be gathered was the total amount of liquid petroleum gas (LPG) used for the plant. The LPG is used exclusively for the forklifts. It became difficult to monitor how much each forklift was using per casting as each forklift is assigned a variety of uses and areas to work in the plant. The LPG consumption would also vary according to the work being done and the driver’s use of the throttle.

Sensitivity on this variable showed that small variations had almost no affect on the output result so it was decided to average the use across the plant on a per kilogram of aluminium basis.

4.4.1.10 Natural Gas

Natural gas is used in the plant / process for melting of scrap, holding of molten metal in the main furnaces, holding of the molten metal at the machines, preheating of the molten metal transfer ladles and space heating in the die maintenance area. A small amount is also used for water heating for the plant toilets and washrooms but this has been ignored in this study because the quantities are very small compared to the other uses.

The CU model considers the metal to manufacture the casting (shipped weight plus losses) to be either brought to the plant as molten aluminium or melted in the plant from ingot and a variable in the model allows this to be changed as a percentage. The results from the previous modelling of the furnace area are then entered into the CU model. This information is in the form of gas required per kilogram per hour of holding time and per kilogram of metal melted. The average time the metal is held for and also the percentage delivered as molten metal (the remainder is considered to be melted in the plant) is entered into the model and an amount of gas per kilogram of aluminium is then multiplied by the shot weight gives an output for the casting and also the functional unit.

From the casting machine, all excessive material including the biscuit, runner, overflows and flash is removed to be remelted in the scrap furnace. This furnace is
specifically designed as a melting furnace and not as a holding furnace. Modelling at the site has shown that this furnace in a very inefficient holding furnace and during the time of this study it was not generally used as a holding furnace being that it was charged with solid material and once molten, it was emptied to be charged again. The input into the Cost-Usage model makes a small allowance for a brief holding period and also for losses during fluxing and raking/cleaning of the furnace. The amount of scrap produced to make each casting is input from the casting details and the output is in the amount of natural gas required to return it to the molten state (where the metal is at an equivalent position to the molten metal delivery and the process starts again). This is also expressed in terms of the functional unit.

The holding of molten metal at the casting machine is achieved by a natural gas fired crucible furnace (or an electric dosing furnace but this has not been modelled although the data has been collected to do so). Data for its consumption was gathered and modelled over one week of continuous use and the results averaged. This is required because the level in the furnace is constantly changing as the metal is used up and refilled as required. The output is expressed in the amount of natural gas required for the casting and per functional unit.

The last part of the model for the natural gas is based on the amount of gas used by the plant for ladle pre-heating and space heating of the tool maintenance area. This is allocated on a per kilogram of aluminium basis.

The Australian Greenhouse Office provides data on the full fuel cycle emission from the use of natural gas. An input is available in the model to enable the calculation of the CO$_2$ emitted from the process as a result of the natural gas usage.

4.4.1.11 Electricity

The main electricity consumers in the plant and the process are the casting machines, air compressors, cooling water system and the heat treatment facility. Other uses for electricity such as lighting for the plant and office use have been included in the model as one group. As part of the study, most of the plant was modelled separately for electricity consumption. All machines had their consumption measured and the separate models detailed the usage of electricity on an hourly basis for the major electrical energy consumers.

The casting machines are of different sizes and the size of the machine may determine how much electricity is used. The age of the machine may also affect its efficiency. The machines are all hydraulically controlled with each machine having at least one hydraulic pump pack. The control systems on the machines are mainly electric with some pneumatics. All of this adds up to the possibility of large variations if measurements were taken from shot to shot and as such the total power required for one hour was measured and the model calculates this into how many castings would have been produced, taking into account the operating conditions mentioned earlier. This gives an output of megajoules per casting and also per functional unit.
Compressed air is used throughout the plant on almost every machine. One central compressor room supplies all of the compressed air for the plant. This comprises three compressors, two air driers and one cooling tower (separate to the main cooling tower). The energy consumption for this total unit was monitored and averaged over a number of days when the plant ran at full capacity (all casting machines running). The Cost-Usage model does not account properly for the compressed air used by the process, as this would be a separate study in itself. What is calculated is the total compressed air energy consumption per day and it is then allocated on a per kilogram of aluminium basis. Also included here is the large amount of energy that is wasted from compressed air leaks and also the time the system runs when the plant is not in use.

As the high pressure die casting process is based on heat it follows that most of this heat is controlled and dissipated by a cooling water system. Cooling water is used to cool the dies in the casting machines, the hydraulic systems and to quench the hot castings when they are removed from the casting machines. The cooling water is pumped around the plant in a closed loop system and then through cooling towers to remove the heat collected from the process. As with the compressed air system, the calculation is the total cooling water system energy consumption per day and it is then allocated on a per kilogram of aluminium basis. The amount of water used by the process is known in some areas but not in all and is not easily found. It is also important to note that the cooling system only runs at full capacity all of the time and is not intentionally shutdown except for maintenance. The CU model calculates the total cooling water system energy consumption per day and it is then allocated on a per kilogram of aluminium basis.

The heat treatment facility was monitored for the power consumption per load and then the number of casting per heat treatment load gives energy consumption per casting. The quench tank, in which the castings are cooled after heat treatment, is electrically heated. The power consumption for the quench tank was monitored for daily consumption and allocated by how many heat treatment loads used the tank in a 24 hour period.

It is difficult to properly allocate the electricity consumption in the plant because of so many shared services that are not monitored, or in some cases, controlled. Plant lighting, heating and cooling is electrically powered and this and other minor users in the plant come under the allocation of ‘other’ users of electricity in the plant. This is allocated on a per kilogram of aluminium basis and converted by the casting weight to a per casting allocation.

Using data available from the Australian Greenhouse Office, an input is available in the model for the full fuel cycle emission factors. This enables the model to calculate the CO₂ emitted from the process as a result of the electricity usage.
4.4.1.12 Other Consumables

Most of the consumables catered for in this part of the model relate to the furnaces including the holding furnace at the machines, molten metal holding furnace and scrap melting furnace.

The machine holding furnace is a natural gas fired, crucible type furnace that uses a ladle to transfer the metal to the casting machine. The consumable items are cast iron ladles and crucibles that have a measurable and finite life. The weights of these are entered into the model with the expected life or mean time between failure (MTBF) of the ladle and crucible. This gives an output of the weight of cast iron per casting and functional unit. Also used are ceramic based coatings on both the ladle and crucible which are used to increase the life since aluminium has a very high affinity for iron and will dissolve it very quickly if left in contact for extended periods. The amounts put on the ladle and the crucible are known but will vary due to application by differing operators. The frequency also does vary according to plant operations as ladles and crucibles are changed from machine to machine. As such the amount used in the plant was averaged and allocated per kilogram of aluminium and per casting.

Fibreglass mesh is used as a filter medium at the crucible and is replaced once per shift. This was allocated to the number of casting produced per shift and then to the functional unit.

At the reverberatory furnaces for melting and holding of the aluminium there are a number of consumables to be allocated such as fluxes, nitrogen, rosco cones, thermocouple sheaths and thermocouples. As all of the metal in the plant is treated with these consumables the allocation was done on a per kilogram of shipped metal basis. The variables associated with these were vast and not constant so further investigation would be necessary to gain a proper insight into them. For example the amount of flux that should be used did not correlate to the amount that was actually used. This indicated that at approximately 50 percent of the time this procedure was supposed to be carried out on this furnace, it wasn’t. This was not isolated and as such the averaging method was thought to be best.

Inside both of the reverberatory furnaces are refractories to retain the heat and contain the molten metal. These are replaced at constant intervals. However, the type of refractory and materials involved will change almost every time this is conducted and as such estimations on weights from refractory demolitions were used although these are thought to be reasonably accurate. The refractories are allocated in a similar way to the energy in that the casting weight plus losses is allocated to the molten metal holding furnace and the scrap weight is allocated to the scrap melting furnace. The repairs and replacement periods are known and an average of metal through the furnace in this time, based on current production levels, is entered into the calculation that yields the amount of refractory per casting and then per functional unit.

Other items included in this part of the model are the steel shot used in the shotblasting operation and freight. The steel shot is used in the process and allocated on a per
casting basis and then per functional unit. The freight is allocated any materials used in the packing of the casting for shipment on a per casting basis.

4.4.1.13 Maintenance

Maintenance of the die and machines is required on a regular basis. This part of the model attempts to take into account the scheduled maintenance of both the dies and the machines. By entering the number of machine cycles between maintenance intervals and also what labour and materials are known to be used, an allocation is made per casting and then per functional unit. This is a very vague part of the model and it is difficult to account for, as most of the maintenance is unscheduled and the records are vague at best. This part of the model is best used for the cost implication, as the emissions are not considered accurate enough to include in the overall assessment.

Part of the maintenance on the machines is the replacement of the hydraulic oil, which leaks and goes to the waste treatment plant. This is captured in the model as a high usage and cost item and allocated on a per kilogram basis.

4.4.1.14 Water

Part of the water usage is calculated with the die lubricant but this does not account for all of the water used by the process. Another major use for water in the plant is the plant cooling water. This is generally a closed loop system but the water used to spray the dies prior to lubrication is plant cooling water. This water goes directly to the waste water system. Other uses for the plant cooling water are to internally cool the dies, hydraulic equipment and casting machine quench tanks. These systems are all closed loop with the water returning to the cooling tower after use.

The amounts of water added to the cooling water system is entered into the model with the amount of waste water processed and the amount of clean water in total entering the plant. As the plant cooling water is used throughout the plant and is a closed loop system, losses from this system are allocated on a per kilogram shipped weight basis.

4.4.1.15 Cooling Water

Added to the water consumption, the plant cooling water has a number of additives added to it to treat the water on a continuous basis. The supplier for these additives was changed in the plant so the information gained was from an interview with the company sales representative and may not be entirely accurate. The supplier was responsible for the water quality in the cooling system and as such no plant records exist of how much of each additive was used or the levels of each additive in the water. The model allows this information to be easily changed if more accurate information becomes available.

The model takes the level each water treatment additive was held at and multiplies it by the usage of water by the plant cooling water system. The information from the MSDS for each water treatment additive gives an indication of how much of each separate
chemical is used and ultimately emitted to the waste water. All waste water in the plant, except for sewage, goes through the plant waste water treatment facility before being passed out to the local water authority for further treatment.

**4.4.1.16 Waste Water Treatment**

The waste water treatment plant on site is used to strip any oils and pH balance the water. Sodium hydroxide is the only chemical added to the water to do this and the model calculates the usage from the use of the sodium hydroxide and how much water passes though the plant each year. This is allocated on a per litre of water through the waste water plant basis and then to the functional unit.

**4.5 CU Model Cost Calculations**

The cost calculation takes the usage output and multiplies it by the cost of that usage. This is common to all of the inputs and where applicable, to the outputs such as waste water where there is a cost of disposal. Items such as scrap aluminium (dross, oily scrap and swarf) have the cost of the lost metal included as the value of the scrap is not usually more than 50 percent of the value of the original metal.

**4.5.1.1 Labour Cost**

Included in the labour cost, as well as the PPE, is all of the on-costs of employment. These include superannuation, insurance, payroll taxes, annual leave, long service and public holidays. These are all added to the hourly rate to give an output cost of each operator per hour. Added to this are the shift loadings which affect the cost of the die casting depending on which shift is made. To remove this an average of all shifts is used to calculate the hourly rate. Also factored into the model is overtime which is generally worked in the plant. The model will also output the cost of the component if it is required to be manufactured in overtime. This is simplistic as many other factors much be considered when overtime is used, most of which would increase this cost but are not considered in this model. For example, when the entire plant must be open to manufacture one component and other overheads cannot be spread across other components.

**4.5.1.2 Maintenance Costs**

The costs of maintenance are spread by the size of the machine in which the die runs as a proportion of the total maintenance budget. Although this is a simplistic approach, it is the same estimate used by the plant when claiming benefits for machines from the research and development department of the plant.

**4.5.1.3 Fixed Overheads**

This aspect is not handled very well in the model but includes items such as site rental and office overheads. The number used by the site is allocated on a per kilogram basis and this is how this cost is also allocated in the model. Fixed overheads are difficult to
evaluate unless the intricacies of the business are known and this is not the case with this study.

4.5.1.4 Deprecation

The depreciation of capital items is touched on in the CU model. To complete the model, the die casting machine is included in a depreciation calculation but the accuracy of this information is low and for this result to be properly considered, more data in this area should be gathered. As further work in the development of the model, the capital of the whole plant should be considered for economic benefit and also to complete the LCA.

4.6 Sample Calculations

These calculations are as they appear in the CU model. Samples are shown because the full list is too big to include. Appendix A has a more detailed list of these calculations.

4.6.1.1 Dross Loss Calculation

200.46 tonnes of dross produced for 2001
80% of this dross comes from the remelt of scrap
200.46 x 0.8 = 160.368 tonnes of dross from scrap
40.092 tonnes of dross from hot metal delivery and melting of ingots.
4143.5 tonnes of scrap melted for 2001
160.368 / 4143.5 = 3.87 %
6627.58 t of hot metal and ingots through the furnaces
4953.88 t of hot metal delivered
40.092 x 25% = 10.024 tonne of dross produced by Reverb 6 (hot metal only)
10.023 / 4953.88 = 0.2 % dross loss from hot metal
1673.7 tonnes of ingot and low pressure metal.
30.069 / 1673.7 = 1.8 % dross loss for other metal, holding furnace skimmings, etc.
Shot weight of hot metal (taken as delivered hot metal) @ 0.2% = 1.9915 x 0.002 = 0.003983 kg
Scrap weight (runner, biscuit and overflows to be remelt in plant) @ 3.87% = (0.8835 + 0.294) x 0.0387 = 0.045569 kg
Scrapped castings = (Reject Rate x shot weight) @ 3.87% = (3.65% x 1.9915kg) x 3.87% = 0.002813 kg
Total Dross loss for each casting = 0.003983 + 0.045569 + 0.002813 = 0.052365 kg.
Financial loss = price paid for aluminium – price received for dross = $2729.56 – (20% x 2729.56) = $2183.648 per tonne = $2.1836 per kg of dross produced.
0052365 kg x $2.1836 = $0.1143 per casting

4.6.1.2 Oily Scrap Loss Calculation

95% of Oily Scrap produced by the High Pressure Process.
64.517 tonnes of Oily scrap produced by plant for 2001
0.95 x 64.517 = 61.291 tonnes of oily scrap produced by HPDC

\[
\frac{61.291}{(4953.88 + 735.4)} \text{ (Molten + Ingot)} = 1.077\%
\]

\[
1.077\% \times \text{casting weight} = 1.077\% \times 0.814\text{kg} = 0.00877 \text{kg}
\]

Financial loss = price paid for aluminium – price received for oily scrap = $2729.56 –

(18\% \times 2729.56) = $2238.24 per tonne = $2.2382 per kg of oily scrap produced.

\[
0.00877 \text{ kg} \times \$2.2382 = \$0.0196 \text{ per casting}
\]

5\% of Oily Scrap produced by LPDC.

\[
\frac{(5\% \times 64.517)}{938.309} = 0.344\%
\]

Total Metal used per shot = shot weight + dross loss + oily scrap loss + (reject rate x

shot wt)

\[
1.9915 + 0.049552 + 0.00877 + (3.65\% \times 1.9915) = 2.12251175 \text{ kg (2.049822 kg)}
\]

As previously mentioned, a more detailed list of the calculations can be found in
Appendix A.

### 4.7 Life Cycle Input

The Life Cycle Input is the information required for the LCA of the process and is essentially the basis of the Life Cycle Inventory. This information is provided from one of the sheets of the CU model.

This is the sheet in the CU model which summarises the inputs to the process. Quantities of materials used in the manufacture of the aluminium die casting are summarised. This information was then fed into the GaBi3v2 software to complete the LCI. This information is in the same form as available in the main sheet of the model but is easier to find the information as it is presented in the form of a table.

### 4.8 Graphical Output

To make the model useful as a tool, a graphical output page was developed which primarily gives a display of the costs of the component. Graphs of the total cost to manufacture the die casting are followed by further breakdowns of these costs. This is an effective management tool for determining where excessive costs are located in the process.

A graph of the electricity cost is followed by the electricity use and finally the CO\(_2\) emitted from the process as a result of the electricity use. This follows from the main part of the model for the full fuel cycle emission of CO\(_2\) from electricity production. The same breakdown of graphs exists for the consumption of natural gas.

### 4.9 Overview of Model Weaknesses

The CU Model has many areas for improvement and its accuracy is difficult to test in some areas. The variations in the data that is entered into the model gives some of the
largest areas for inaccuracy but there are also some areas where estimations have been made in place of unavailable data that would be improved with more work in these areas.

The maintenance allocation in the model is very much an estimation based on very limited data and interviews with personnel. Proper details of all repairs in the plant would reveal a clearer picture of the costs in this area and also the emissions in the form of scrap and waste to landfill. Some of this data is available but was not analysed as part of this study.

Fixed overheads have been estimated in the model. This is because of the unavailability of information in this area due mainly to confidentiality. For an industrial partner using this model, fixed overheads are usually allocated on a dollar per functional unit basis so this could easily be added in further work. To assign the fixed overheads on an activity based allocation would be more accurate and could be useful to discover the real costs of the die cast component.

The allocation of compressed air should be activity based but it is not due to the large uncertainties in this area. Since approximately 20 percent of the air used in the plant is due to leaks in the system it becomes difficult to allocate this. More work on this part of the model is possible to establish a base load of compressed air which could be allocated on a functional unit basis and then an activity based component for the actual use of the compressed air. A similar system should also be developed for the use of cooling water in the plant.

General electricity allocation has been modelled extensively in the plant but due to its random use in many areas of the plant, precise allocations of its use are difficult and have been ignored in this iteration of the model. This is a great opportunity for improvement as electrical energy and the emissions from its generation are a large proportion of the total emissions from the process.

The ease of use of the model could be greatly increased by the writing of macros and introducing some visual basic programming. This would also protect the source data and code for later use.
5 LCA by Commercial Software

5.1 Outline of Chapter

A commercial software package was purchased along with a database of information on materials. This chapter goes through the setting up of the model within the software, entering the results from the Cost-Usage model and other data which was gathered. The presentation of results from the model are shown at the end of the chapter.

5.2 Software Description

5.2.1 General

The GaBi3v2 software was developed by the University of Stuttgart initially and is now marketed by PE Product Engineering GmbH. It is software that has been developed specifically for LCA study and has many features which make it good for modelling processes as is the case with this study. The software was purchased mainly for this reason and also because the same software was also purchased by another project within CAST by the CSIRO. As this study was sharing knowledge with the other project is was decided to keep the software common as LCA software is not a well developed field and differing software is generally not compatible for the sharing of data.

The GaBi3v2 software requires the user to input a plan of the process under study which compromises all of the major components of the process. The plan is the framework of the model off which everything else is hung. From the plan, input and output data is fed into the major (and minor) elements of the process. This data is linked to the GaBi3v2 database which holds all of the relevant information on the inputs and outputs of the process. When complete the plan can be analysed for emissions to air, water, et cetera, for global warming potential, human toxicity, et cetera. The outputs can be in the form of table or graphical.

5.2.2 Data

The plan of the process had the different elements of the process linked so as the data in one process must be compatible with the next process. For example, the output from the ‘furnace’ element will all be in the form to produce one kilogram of aluminium which links to the ‘metal transfer’ element which requires more than one kilogram of aluminium and thus will scale the input to match. The key is that these elements can only be linked by the common input/output of the aluminium. Each element in the process can produce more than one output but to link it to another process the inputs and outputs must match. This is one of the more difficult aspects of the software to handle and requires careful planning to avoid mismatch of inputs/outputs.
5.2.3 Plans and information Input

The plan interconnects the different elements in a process with links that follow the flow of material in the process. The thickness of the link in the display is proportional to the size of the flow.

5.2.4 Output

The output from the model is called the ‘balance’ and gives the results from all of the inputs and outputs into global warming potential, human toxicity potential, carcinogenic substances or 22 other equivalent values. This is broken down into up to four levels of depth.

5.3 Overview of Die Casting GaBi3v2 Model

This model was created as the life cycle inventory / life cycle assessment phase of the study. While the Cost-Usage was created with other processes in mind and to be possible be used again at a later time, the GaBi3v2 model was created purely for the purpose of this study and it lacks the depth of documentation which could give it use at a later time. It is a complex piece of software, modelling a complex process and as such it is difficult to follow. The validation and testing of the model was very difficult because there is no data (except what has been collected for this study) to compare the results against. The model has been peer reviewed during its development but this does not guard against mistakes.

The GaBi3v2 software works by having a plan of the process that is made up of other plans and processes. The processes are made up of inputs and outputs which are called ‘flows’ which are the information that makes up the GaBi3v2 proprietary database.

The GaBi3v2 database has a simplified die casting part but this result was very brief and not considered accurate since it was a calculated result and has hence been ignored.
5.4 Input of Process – Plan

Aluminium Supplier
GaBi 3 process plan

Figure 5-1: Example of GaBi3v2 plan

Figure 5-1 shows a part of the model developed but not used, showing the secondary aluminium smelter. Each box represents part of the process. For simplicity, this whole plant is one box with the electricity and natural gas going in to the process and the molten metal transport coming out of the process. The lines which can be seen interconnecting the boxes are mass flow with the thickness determined by the mass in kilograms as required in the contribution to the final product of one kilogram of cast product. These flows can be alternately represented as energy, number of pieces or volume of material.

The flow of the process can be seen as the input of the electricity (from brown coal) and the natural gas into the plant of the smelter. By connecting these to the plant, their inputs and outputs are considered for the balance calculation.

To input the plan of the die casting process into the GaBi3v2 model required a transfer of the flow chart of the process into the GaBi3v2 software.

5.4.1 Processes

5.4.1.1 Created Process

Figure 5-2 shows one of the processes created within the software. Each process has an individual name and also has the country of origin and the date of the data stored with it (since these are two important variables with any LCA data). The table of inputs into the process has a number of ‘flows’ which are placed into the table from the
database. If the flow which is required is not present in the database then it must be created. Each flow is assigned the quantity of its units and also the amount of each required to make the functional output which in the case of Figure 5-2 is one kilogram of secondary aluminium. As such it can be seen that to make this output requires thermal energy from natural gas, electricity, aluminium scrap and so on down the table of inputs. The table of outputs gives the main output and also any other associated outputs that are emitted from the process. This data is not given by the software and must be entered in the course of the model construction.

![GaBi3v2 Secondary Aluminiums Smelting Material recovery](image)

**Figure 5-2 : Example of GaBi3v2 created process**

### 5.4.1.2 GaBi3v2 Processes

The GaBi3v2 processes are part of the GaBi3v2 proprietary database and as such no real history is known about them aside from the limited information stored. The data in the GaBi3v2 database processes is aggregated data. The GaBi3v2 processes mostly emanate from Europe with limited data from the United States also. Some data is available from Australia but the location with Australia is not given and as such this data has limited use. This is because of the aggregated data and the differing energy sources from state to state.

The process in Figure 5-3 is typical of one of the database processes where most of the data comes from literature or is calculated but little else about the data is known. If by chance this type of process closely matches what is used in the process under study, it can be modified to suit, but because of the nature of aggregated data this will always be an estimate. The data in figure 5-3 can be seen to be from Germany in the
year 1997 and although some of this may be relevant to a similar process conducted in Australia, many of the flows are recorded in such small numbers that any inaccuracies would greatly affect the result so any manipulation of this data would have to be conducted very carefully.

The processes are made up of flows that are also part of the GaBi3v2 proprietary database. There will usually be at least one flow in each process which is tracked through the plan. To track a flow will enable the process boxes in the plan to be linked. If the flow in the process is not tracked the processes cannot be linked in the plan.

5.4.1.3 Supplied - Other Data

The GaBi3v2 database does not include much data that is relevant to die casting or Australia. As energy is one of the main contributors to the die casting process and it was also thought to be one of the main emitters to the environment it was considered important to get accurate data in these areas.

A lot of work has been done in the area of energy by the RMIT – Centre for Design and this data has been made available in the public domain. Usually it would cost a lot of money to buy this type if disaggregated data and for it to be available has helped this study a great deal. The data was available either in the SimaPro format or as a spreadsheet. Either way it could not be automatically entered into the GaBi3v2 database so a lot of time was spent placing all of this information into processes for natural gas transmitted, Victorian base load electricity (brown coal generated) and
liquid petroleum gas (LPG) free refinery. This data is considered to have a high degree of accuracy.

### 5.4.1.4 GaBi3v2 Flows

![Figure 5-4: Example of GaBi3v2 database flows](image)

Figure 5-4 shows two of the flows from the GaBi3v2 database in detail. These can be edited if the information is found to be erroneous or has changed in the time since the data was collected. The name of the flow is how the flow will be identified in the database. The chemical formula can be stored for extra information. The reference quantity is how the flow is measured in both the database and the processes in which it is used. Additionally to this information are the equivalent factors that are so important in any LCA data. The examples in figure 5-4 show equivalences for global warming potential and acidification potential. Unfortunately not all of the data in the database has this information and it is this information that is guarded very closely by those who have it and it is considered to be very valuable. As such this type of data can either be purchased for a very high price or researched. This would require a separate study in itself and reference to this can be found in Chapter 7 of this document.

Any data not found in the database can easily be created in the GaBi3v2 format. The format is not transferable to other software and the data in other software is not transferable to GaBi3v2. This has resulted in a lot of extra work transferring data that is available in the public domain into the GaBi3v2 software.

### 5.4.2 Output of Results

Once all of the processes in the plan are complete and all of the flows are balanced with correct amounts of mass and energy, the plan can be analysed (called a ‘balance’ in the software) and an output of results formulated.

The results are shown in a table format and can be presented in one of 23 quantities which include global warming potential, human toxicity potential, acidification potential, etcetera and the breakdown can be shown on a number of different levels. The output
can be simply an equivalent number or a breakdown showing which processes contribute to that number. This breakdown corresponds to the plan which the analysis corresponds to. The results are dependant on the database for their accuracy so if the database is incorrect or incomplete then the result will not be as accurate as may be required.

### 5.4.2.1 Table

![Figure 5-5: Example of GaBi3v2 results table](image)

It can be seen from Figure 5-5 that the global warming potential after 100 years (GWP 100) of this process is 0.96912 kg CO\(_2\) eq and this is broken down further to see that most of this contribution comes from the thermal energy from natural gas of which it is all emissions to air. These emissions to air are mainly inorganic emissions to air, which upon further analyses, is the CO\(_2\) emission from the burning of the natural gas in the furnace.

### 5.4.2.2 Graphical

For a clearer picture of the results a graphical output is also available (Figure 5-6) showing the same results as Figure 5-5. This more clearly demonstrates the main offending process and also the type of emission.
Figure 5-6: Example of GaBi3v2 results graph
6 Case Study

6.1 Outline of Chapter

This chapter sets out the application of the Cost-Usage (CU) Model for two different aluminium components, both manufactured using the high pressure die casting process. The Casting AA and the Casting BB are both cast in the same plant using different sized die casting machines and different finishing processes. The data available for these components is actual data. The Casting AA is the only component to be modelled using the commercial GaBi3v2 software as the LCI output from the CU model demonstrates the points to be made more clearly. The chapter concludes with a comparison between the results for the two castings.

6.2 Description of Process at Site

6.2.1.1 Metal

The aluminium used in the plant is secondary aluminium (known as ADC12 aluminium alloy), which is delivered to the plant from one supplier as molten metal or as ingot from any supplier, anywhere in the world. The metal used is not further processed with any other alloying elements once received in the plant. The ingot will be at room temperature having being cast at the supplier’s foundry or the molten metal will be at approximately 720°C. The aluminium and the transport of the aluminium to the site is outside the system boundary of this study and further reasoning of this can be found in chapter 7. The site received 87 percent of all its aluminium molten form for the year under study.

6.2.1.2 Furnace

Whether the metal arrives in the plant in ingots or as molten, it is all placed into a furnace. The site uses gas fired reverberatory wet bath furnaces to melt and hold all of its metal. The molten metal is delivered into a holding furnace that is very efficient (in relative terms for the type of furnace design) at holding molten metal but is not capable of melting metal. Ingots (and scrap) are placed into a smaller capacity melting furnace. Both furnaces are lined with refractory and the metal in the furnaces will be cleaned at least once daily using nitrogen gas and flux. It will be raked after cleaning to remove the dirty metal and the dross. The amounts of dross produced will depend on the origins of the metal with scrap returns creating large amounts of aluminium rich dross and ingots or liquid metal delivery creating small amounts of dry powdered dross. The different types of dross are only relevant to the metal recycler where the rich dross has a higher content of aluminium than the dry dross.
6.2.1.3 Filtering / Cleaning / Transfer

The molten metal is then transferred to the machines. A LPG fuelled fork truck with a ladle attached to the front is used to move the metal from the reverberatory furnace to the crucible holding furnace at the machine. The metal will be cleaned between these two furnaces using flux and nitrogen gas in a rotary degasser. When poured from the forklift ladle to the crucible holding furnace it will pass through a fibreglass mesh filter.

6.2.1.4 Machine Holding

The metal is held at the machine in gas fired crucible type furnace. The crucible furnace uses a robotic arm with a ladle attached to transfer the metal from the furnace to the shot sleeve. The ladle tilts in the furnace to meter the correct amount of metal to transfer. The ladle is made from cast iron and will be replaced every 5 days. The cast iron crucible will last for approximately five months but will be replaced prior to failure due to the consequences of a failure and subsequent metal spill and potential fire. A coating is applied to minimise the reaction between the cast iron and the molten aluminium prolonging the life of the ladle and the crucible.

6.2.1.5 Casting

The high pressure die casting machine is electrically powered using a hydraulic system to move the machine and to force the metal into the die. The casting machine has consumable items made from tool steel and also the die itself which is a combination of cast steel and tool steel. After the metal is poured into the machine it is forced into the die where it solidifies with the help of cooling water which runs through the die to remove some of the heat. After solidification, the die will open and the cast component is ejected from the die.
The die surfaces will then be sprayed with die lubricant to aid in the release of the next cast component from the die. Figure 6-1 shows a robot spraying the die surfaces with lubricant. The lubricant is suspended in water, which upon hitting the die, evaporates leaving a thin coating of lubricant on the die. The die may need to be first sprayed with water to lower the surface temperature since the lubricant will only stick to the die surface between a range of temperatures (approximately $150^\circ C - 250^\circ C$).

### 6.2.1.6 Finishing

The number of finishing operations available to a die casting is very extensive. Nearly all die castings will be trimmed to remove the biscuit, runner and overflows and then fettled to remove sharp edges and excess material. From here the casting can go through any number of processes according to what the end product is required to do. Shotblasting the casting will give a uniform surface finish whilst electroplating or anodising will give the casting a coloured appearance. The inputs and outputs from these processes are as endless as the operations chosen for a particular casting.

The finishing operations considered for this study were trimming, fettling, heat treatment (for stress relieving), shotblasting, leak testing, and broaching.
6.2.1.7 Packing

All castings will be packed in or on something to be shipped to the customer. For some castings it will be a re-useable steel stillage or pallet and for others it may be a wooden pallet with plastic sheeting for disposal at the customer’s plant. The packing can have significant environmental aspects that should be considered. This study considers packing from the materials used and is not concerned with the transport of the final cast product to the customer. Reusable pallets and stillages are used in this study and become irrelevant since transport is not considered. If transport were considered, this type of packaging may not be the best economically or environmentally.

6.2.2 Description of Plant Used at Site

Many parts of the die casting process use different types of equipment. The following gives the important features of the equipment used at the site.

6.2.2.1 Site General Description

The site studied is a large die casting facility located in Victoria, Australia. It employs approximately 150 people and is operational 24 hours per day across three shifts. The plant operates normally 5 days per week, 48 weeks per year.

Two die casting processes are used at the site, high and low pressure die casting. The high pressure process accounts for 85 percent by shipped weight of castings produced.

6.2.2.2 Die Casting Machine

The high pressure die casting machines are electrically powered and hydraulically driven. Using a water-glycol fluid (for fire resistance), the hydraulic systems on the machine can have more than one pump and have bladder type accumulators to achieve the very high pressures required to force the molten metal into the die.

The machines used at the site range in size from 800 tonne clamping force to 2250 tonne clamping force. The machine range in age between 10 and 20 years old and have average uptimes of 80 percent.

Machine maintenance is performed by company personnel on regular intervals to reduce breakdowns.

6.2.2.3 Dies

The company designs its own dies but has them manufactured off site. Die maintenance is performed on site by company personnel. The die inserts which come into contact with the molten metal are manufactured from H13 tool steel which is heat treated for toughness and hardness. The bolsters which hold the inserts and connect to the die casting machine are made from cast P20 steel.
The life of a set of inserts usually lies between 100,000 and 200,000 shots but will vary depending on the complexity of the part and the customers requirement for surface finish of the component. Inserts will fail from thermal fatigue or corrosion from the cooling water channels that are internal to the die surface. The bolster will usually last for at least the life of three sets of inserts but premature failure will occur if the design is incorrect as the bolster holds the mechanical stresses of the die.

6.2.2.4 Cooling Water System

The cooling water used in the plant is a closed loop system which circulates the water around the plant and through a cooling tower. The cooling water is used to remove heat from the die casting dies, the hydraulic systems of the casting machine and other machines, quenching of castings and also is sprayed on to the die surface for cooling.

The cooling system uses approximately one million litres of water per week, most of which goes through the waste water treatment facility located on site. Large amounts of water are lost through evaporation. Chemicals are added to water in the cooling system by an outside contractor. These are corrosion inhibitors, anti foaming agents, biocides and others required to keep the cooling water clean and prevent build up of material in the system which can reduce the flow or block the cooling channels and heat exchangers.

The system is electrically powered and uses two 90 kW pumps for water circulation. The cooling water system is permanently operational, even when the plant is not running.

6.2.2.5 Compressed Air System

The plant uses two electrically powered 200 kW and one 120 kW screw type compressors to deliver approximately 700 litres of air per second at 6 – 7 bar pressure. A management system cycles the compressors as only two are required at one time and the duty cycle is adjusted between loaded and unloaded conditions as required. The management system is not reliable and is often in maintenance mode where the plant pressure rises to 7 bar and only the two larger compressors are used. This is very inefficient and costly. Attached to the compressors are two air dryers and a separate cooling water system with cooling tower.

Compressed air is used throughout the plant to drive small, low power operations. One of the main uses of the air is to remove water from the die surface prior to closing at the end of the lubrication cycle.

6.2.2.6 Heat Treatment Facility

The heat treatment is conducted by eight electric resistance furnaces with two electrically heated quench tanks. For the high pressure process it is uncommon to heat treat the casting because the alloys are generally not heat treatable and imperfections in the castings from the casting process can damage the casting if heat treated. With the right casting alloy and casting design it is possible to heat treat for increased
strength and toughness high pressure die cast components but it not conducted in this plant. The heat treatment facility is however used to stress relieve high pressure castings as the process can leave considerable stress in the casting causing deformation.

6.2.2.7 Furnaces

The molten metal which enters the plant is delivered into a 20 tonne holding furnace. This is a natural gas fired reverberatory type furnace with clay based refractories. The refractory well where the molten metal is delivered is replaced every 2 years and the whole furnace is relined every 10 years.

The melting of metal is performed in a four tonne capacity natural gas fired reverberatory furnace at a rate of one tonne per hour. The refractory walls are replaced every three years and the entire furnace is relined every 8 years. This variable will change depending on furnace use and damage which can be caused to the refractories by incorrect operation.

The furnace temperature is in all of the reverberatory furnaces is controlled with thermocouples which are placed inside a cast iron sheath to protect them from the aluminium. The thermocouple and sheath are replaced once per week or as required if damaged prior to this.
### Table 6-1: Plant input variables

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure Molten Metal (tonnes):</td>
<td>4953.88 t</td>
</tr>
<tr>
<td>High Pressure Ingots (tonnes):</td>
<td>735.40 t</td>
</tr>
<tr>
<td>Low Pressure Aluminium (tonnes):</td>
<td>938.31 t</td>
</tr>
<tr>
<td>Dross (tonnes):</td>
<td>200.46 t</td>
</tr>
<tr>
<td>$ % $ of Al:</td>
<td>20%</td>
</tr>
<tr>
<td>Oily Scrap (tonnes):</td>
<td>64.52 t</td>
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<td>$ % $ of Al:</td>
<td>18%</td>
</tr>
<tr>
<td>Turnings (tonnes):</td>
<td>35.53 t</td>
</tr>
<tr>
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<td>50%</td>
</tr>
<tr>
<td>Hours Available each day:</td>
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<tr>
<td>Production Days per Year:</td>
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</tr>
<tr>
<td>% of Dross Produced from Scrap Furnace:</td>
<td>80%</td>
</tr>
<tr>
<td>% of Dross Produced by Hot Metal:</td>
<td>5%</td>
</tr>
<tr>
<td>% of Dross from other metal:</td>
<td>15%</td>
</tr>
<tr>
<td>% of Oily Scrap from HPDC:</td>
<td>95%</td>
</tr>
<tr>
<td>% of Oily Scrap from LPDC:</td>
<td>5%</td>
</tr>
<tr>
<td>Steel Scrap Produced by Plant 2001:</td>
<td>24.82 t</td>
</tr>
<tr>
<td>Labour Shift Loading Afternoon Shift:</td>
<td>18%</td>
</tr>
<tr>
<td>Overtime Loading Night Shift:</td>
<td>30%</td>
</tr>
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</tr>
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</tr>
<tr>
<td>Overtime Loading Third Level:</td>
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</tr>
<tr>
<td>Total Number Of Employees:</td>
<td>154</td>
</tr>
<tr>
<td>Number of Machine Operators:</td>
<td>75</td>
</tr>
<tr>
<td>Direct (Operators, Maint., Toolroom):</td>
<td>110</td>
</tr>
<tr>
<td>Indirect (Staff, Quality, Purchasing):</td>
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</tr>
<tr>
<td>Hourly Rate: $ 20.00</td>
<td></td>
</tr>
<tr>
<td>Superannuation %:</td>
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<tr>
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<td>Annual Leave:</td>
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<td>Public Holidays:</td>
<td>4%</td>
</tr>
<tr>
<td>Hours Worked per Shift:</td>
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<tr>
<td>PPE Overalls:</td>
<td></td>
</tr>
<tr>
<td>Number per Week per Operator:</td>
<td>2</td>
</tr>
<tr>
<td>PPE Glass Gripper Gloves:</td>
<td>11165</td>
</tr>
<tr>
<td>Weight of Glass Gripper Gloves:</td>
<td>0.150 kg</td>
</tr>
<tr>
<td>PPE Cotton Gloves Used per Year:</td>
<td>45858</td>
</tr>
<tr>
<td>Weight of Cotton Gloves:</td>
<td>0.100 kg</td>
</tr>
<tr>
<td>Ear Plugs Number Used per Year:</td>
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</tr>
<tr>
<td>Labour - 1 ladle to casting m/c (min):</td>
<td>15 min</td>
</tr>
<tr>
<td>Weight of Aluminium in Ladle (kg):</td>
<td>500.00 kg</td>
</tr>
<tr>
<td>Labour - 1 scrap bin to furnace (min):</td>
<td>5 min</td>
</tr>
<tr>
<td>Weight of Aluminium in Bin (kg):</td>
<td>500.00 kg</td>
</tr>
<tr>
<td>Labour - flux and rake one furnace (min):</td>
<td>60 min</td>
</tr>
<tr>
<td>Fibreglass Filter Mesh used / shift (m2):</td>
<td>0.25 m$^2$</td>
</tr>
<tr>
<td>Cast Iron Holding Crucible life (months):</td>
<td>5 mth</td>
</tr>
<tr>
<td>Forklift Cost LPG use 2001(litres):</td>
<td>40735 lt</td>
</tr>
<tr>
<td>Natural Gas:</td>
<td></td>
</tr>
<tr>
<td>Furnace Gas Usage Per Hour (GJ /t/ Hr):</td>
<td>0.08 GJ/Hr</td>
</tr>
<tr>
<td>Av. Holding Time (Hr bw del / 2) (Hr):</td>
<td>6 Hrs</td>
</tr>
<tr>
<td>Melt Furnace Gas Usage (GJ /tonne):</td>
<td>3.59 GJ/t</td>
</tr>
<tr>
<td>Holding at Machine:</td>
<td></td>
</tr>
<tr>
<td>Other per kg Al Sold:</td>
<td>0.00015 GJ</td>
</tr>
<tr>
<td>Natural Gas Full Fuel Cycle kg CO2 / GJ:</td>
<td>54 Kg</td>
</tr>
<tr>
<td>Electricity:</td>
<td></td>
</tr>
<tr>
<td>Compressor Power Use / 24 hrs (MWHr):</td>
<td>8.36 MWHr</td>
</tr>
<tr>
<td>Cooling Water Power Use/24 hrs (MWHr):</td>
<td>5.41 MWHr</td>
</tr>
<tr>
<td>Other per kg Al Sold:</td>
<td>0.0002 MWHr</td>
</tr>
<tr>
<td>Electricity End use kg CO2 per GJ:</td>
<td>407.5 kg</td>
</tr>
<tr>
<td>Other Consumables:</td>
<td></td>
</tr>
<tr>
<td>Sewage Disposal % of water used:</td>
<td>22.00%</td>
</tr>
<tr>
<td>Water used in Cooling System/day (kg):</td>
<td>190000 kg</td>
</tr>
<tr>
<td>Total Other Water used in per day (kg):</td>
<td>80000 kg</td>
</tr>
<tr>
<td>Waste Water Disposal per day (kg):</td>
<td>170000 kg</td>
</tr>
<tr>
<td>Crucible Coating Peel Coat Use for plant (kg):</td>
<td>1110 kg</td>
</tr>
<tr>
<td>Ladle Coating Felpro Use for plant (kg):</td>
<td>345 kg</td>
</tr>
<tr>
<td>Melting and Transfer Consumables:</td>
<td></td>
</tr>
<tr>
<td>Ross Cones used per ladle:</td>
<td>1</td>
</tr>
<tr>
<td>Average Aluminium size of ladle (kg):</td>
<td>500 kg</td>
</tr>
<tr>
<td>Flux (reverb furn.)Total Used for Plant (kg):</td>
<td>2900 kg</td>
</tr>
<tr>
<td>Degas Flux Total Used for Plant (kg):</td>
<td>2800 kg</td>
</tr>
<tr>
<td>Nitrogen (bulk use) Total Used for Plant (lt):</td>
<td>16746 lt</td>
</tr>
<tr>
<td>Reverb Therm Sheath Total Used for Plant :</td>
<td>107</td>
</tr>
<tr>
<td>Weight of Thermocouple Sheath:</td>
<td>4.23 kg</td>
</tr>
<tr>
<td>Reverb Thermocouple Total Used for Plant :</td>
<td>162</td>
</tr>
<tr>
<td>Scrap Furnace Refractory Life (years):</td>
<td>8</td>
</tr>
<tr>
<td>Weight of Refractory full reline (kg):</td>
<td>15,000 kg</td>
</tr>
<tr>
<td>Weight of Refractory wall reline (kg):</td>
<td>5,000 kg</td>
</tr>
<tr>
<td>Weight of Refractory wall reline (kg):</td>
<td>10 yrs</td>
</tr>
<tr>
<td>Weight of Refractory full reline (kg):</td>
<td>20,000 kg</td>
</tr>
<tr>
<td>Weight of Refractory wall reline (kg):</td>
<td>7,000 kg</td>
</tr>
<tr>
<td>Crucible Weight (kg):</td>
<td>1,000 kg</td>
</tr>
</tbody>
</table>
Chapter 6
Case Study

The information in Table 6-1 is the general plant information that was entered into the Cost-Usage model. This table has omitted cost (due to confidentiality) although it is part of the input parameters. For each item which is entered into the model, there is also a cost entered. The information in Table 6-1 is common to any casting which is manufactured in the plant under study. A separate set of variables pertains to the individual castings. This information came from the plant under study for the calendar year 2001 and is accurate usage information.

6.3 Casting AA

![Complete Casting AA casting spray](image)

6.3.1 Product Description

The Casting AA is an automotive component used on an automatic transmission case as a bearing cover. It is cast in an 800 tonne casting machine as a twin cavity die. It has a shipped weight of 0.814 kilograms and the runner, biscuit and overflows weigh 1.178 kilograms giving a total shot weight of 1.992 kilograms. The yield of the casting is 40.87 percent.

After casting is has a high number of finishing operations which are, in order; trimming, fettling / grinding, shotblasting, automatic inspection, heat treatment (stress relieving) and packing. For the year under study 335,228 castings were produced of which 3.65
percent (12,228) were rejects. The rejected casting can only be remelted as scrap and cannot be recovered for sale.

6.3.2 Casting AA Input Variables

<table>
<thead>
<tr>
<th>Percentage Uptime:</th>
<th>80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Cavities in Die:</td>
<td>2</td>
</tr>
<tr>
<td>Cycle Time of Machine (sec):</td>
<td>60</td>
</tr>
<tr>
<td>Shipped Weight (kg):</td>
<td>0.814 kg</td>
</tr>
<tr>
<td>Biscuit and Runner (kg):</td>
<td>1.767 kg</td>
</tr>
<tr>
<td>Shot Sleeve Diameter (mm):</td>
<td>85 mm</td>
</tr>
<tr>
<td>Standard Biscuit Length (mm):</td>
<td>20 mm</td>
</tr>
<tr>
<td>Average Biscuit Length (mm):</td>
<td>20 mm</td>
</tr>
<tr>
<td>Overflow Weight (kg):</td>
<td>0.588 kg</td>
</tr>
<tr>
<td>Good Castings Produced 2001:</td>
<td>323000</td>
</tr>
<tr>
<td>Reject Casting Produced 2001:</td>
<td>12228</td>
</tr>
<tr>
<td>Actual Weight of casting:</td>
<td>0.814 kg</td>
</tr>
<tr>
<td>Labour - Number of Machines Supervised:</td>
<td>5</td>
</tr>
<tr>
<td>Castings Per Heat Treat Load:</td>
<td>1000</td>
</tr>
<tr>
<td>Heat Treat Labour (minutes total per load):</td>
<td>100.00</td>
</tr>
<tr>
<td>Packing Labour (minutes per Heat Treat Load):</td>
<td>100.00</td>
</tr>
<tr>
<td>Labour Time to Validate One Casting (min):</td>
<td>30 min</td>
</tr>
<tr>
<td>Castings validated per 24 hour period:</td>
<td>2</td>
</tr>
<tr>
<td>Bolster Expected Life (shots):</td>
<td>800000</td>
</tr>
<tr>
<td>Total weight of bolster (both halves) (kg):</td>
<td>5,000 kg</td>
</tr>
<tr>
<td>Inserts Expected Life (shots):</td>
<td>200000</td>
</tr>
<tr>
<td>Total Weight of Inserts:</td>
<td>400 kg</td>
</tr>
<tr>
<td>Per Cavity (kg):</td>
<td>200 kg</td>
</tr>
<tr>
<td>Flow Rate / Lube Spray Nozzle (l/min):</td>
<td>2.5 l/min</td>
</tr>
<tr>
<td>Flow Rate / Water Spray Nozzle (l/min):</td>
<td>2.5 l/min</td>
</tr>
<tr>
<td>Number of Water Spray Nozzles:</td>
<td>12</td>
</tr>
<tr>
<td>Number of Lubricant Spray Nozzles:</td>
<td>12</td>
</tr>
<tr>
<td>Die Lube Spray Time (sec):</td>
<td>3 sec</td>
</tr>
<tr>
<td>Water Spray Time (sec):</td>
<td>3 sec</td>
</tr>
<tr>
<td>Tip Lube Amount per Shot (lt):</td>
<td>0.002 lt</td>
</tr>
<tr>
<td>Warm up Lube - Amount Used 2001 (lt):</td>
<td>920 lt</td>
</tr>
<tr>
<td>Shot Sleeve Shots bw reconditioning:</td>
<td>40000 shots</td>
</tr>
<tr>
<td>Max. no. of Recon. per sleeve:</td>
<td>2</td>
</tr>
<tr>
<td>Weight of Shot Sleeve (kg):</td>
<td>50 kg</td>
</tr>
</tbody>
</table>

**Electricity:**

- 80T Mach. Power Use / Hour (MWHr): 0.032 MWHr
- Shotblaster Electricity use / hour (MWh): 0.006 MWHr
- Heat Treatment: 1000
- Power Consumption per Load (MWHr): 0.25 MWHr
- Quench Tank tot. Pwr Use / Day (MWHr): 1.00 MWHr
- Shot Usage for Plant (kg): 25250
- Number of Shotblasters for plant: 6
- Cast Iron Ladle life (days): 5
- Cast Iron Ladle Weight (kg): 9.35 kg
- No. of toolmakers required: 1
- Machine Maintenance Costs: 40000
- Months bw Preventative Maintenance: 3
- No. of shifts required: 1

**Table 6-2: Casting AA input variables**

In the plant studied, this component is considered a high volume casting and is made exclusively on one machine. It is not a complex casting although due to tight tolerances it can be difficult to manufacture. The variables shown in table 6-2 are unique to the Casting AA casting and once again the cost element of these variables has been omitted from the table.
6.3.3 Cost-Usage Outputs

The outputs of the Cost-Usage Model are in a number of forms. Of most use to industry is the breakdown of cost which will not be published. Of the material in this area that is shown is graphical output based on energy consumption and full fuel cycle emissions based on this energy consumption. Also produced from the model is the usage of all materials which to be placed into the GaBi3v2 model as can be seen in Table 6-3. The numbers in the table represent the materials used to make one kilogram of aluminium casting (the functional unit of the study) using the high pressure process. The italic numbers are the ingredients of the material above in the table.

The quantities shown in Table 6-3 are measured to the sixth decimal place. None of the variables used were measured to this accuracy and many of them could not be measured to this accuracy in the plant even if required. The reason behind this level of accuracy is that for many of these variables a very small amount is a lot in terms of the cost of the material and its environmental impact. Thus when a larger number is measured and averaged to get this data, this level of accuracy could be important. Rather than round some of the data, all of the data was preserved for entry into the GaBi3v2 model.
### 6.3.3.1 Outputs to GaBi3v2 Model Casting AA

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount</th>
<th>Unit</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour per kg Al Shipped</td>
<td>1.436996</td>
<td>min/kg</td>
<td>Common</td>
</tr>
<tr>
<td>Cotton per kg Al Shipped</td>
<td>0.000757</td>
<td>kg</td>
<td>Gloves</td>
</tr>
<tr>
<td>Rubber per kg Al Shipped</td>
<td>0.000160</td>
<td>kg</td>
<td>Gloves</td>
</tr>
<tr>
<td>Weight of P2O5 (or Cast Steel) per kg of Al Shipped</td>
<td>0.003839</td>
<td>kg</td>
<td>Die Bolster</td>
</tr>
<tr>
<td>Weight of H13 per kg of Al Shipped</td>
<td>0.000614</td>
<td>kg</td>
<td>Die Inserts</td>
</tr>
<tr>
<td>Die Lube Water per kg Al Shipped</td>
<td>1.836263 litres</td>
<td></td>
<td>Die Spray Water</td>
</tr>
<tr>
<td>Die Lube per kg Al Shipped</td>
<td>0.012977</td>
<td>litres</td>
<td></td>
</tr>
<tr>
<td>Alkenylsuccinic Acid Derivate 1-5% per kg Al Shipped</td>
<td>0.000649 litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon Oil &gt;20% per kg Al Shipped</td>
<td>0.002595</td>
<td>litres</td>
<td></td>
</tr>
<tr>
<td>Polypropylene wax 10-15% per kg Al Shipped</td>
<td>0.001947 litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water &gt;50% per kg Al Shipped</td>
<td>0.006489 litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tip lube per kg Al Shipped</td>
<td>0.001229 litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petroleum Oil 96% per kg Al Shipped</td>
<td>0.001179 litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite 4% per kg Al Shipped</td>
<td>0.000049 litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silver Grease per kg Al Shipped</td>
<td>0.000199 litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral Oil 60-100% per kg Al Shipped</td>
<td>0.000193 litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stoddard Solvent 0-3% per kg Al Shipped</td>
<td>0.000006 litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kg of H13 per kg of Al Shipped</td>
<td>0.000512 kg</td>
<td></td>
<td>Shot Sleeve</td>
</tr>
<tr>
<td>Kg of Copper per kg of Al Shipped</td>
<td>0.000152 kg</td>
<td></td>
<td>Tip</td>
</tr>
<tr>
<td>Kg of H13 per kg of Al Shipped</td>
<td>0.000045 kg</td>
<td></td>
<td>Sprue Post</td>
</tr>
<tr>
<td>Kg of H13 per kg of Al Shipped</td>
<td>0.000129 kg</td>
<td></td>
<td>Sprue Bush</td>
</tr>
<tr>
<td>LPG - Litres per kg Al Shipped</td>
<td>0.006438 litres</td>
<td></td>
<td>Forklift</td>
</tr>
<tr>
<td>Natural Gas Total used per kg of Aluminium Sold</td>
<td>8.391421 MJ</td>
<td></td>
<td>Common - Metal</td>
</tr>
<tr>
<td>Electricity Total used per kg of Aluminium Sold</td>
<td>5.170948 MJ</td>
<td></td>
<td>Common</td>
</tr>
<tr>
<td>Total Water used per kg Al sold</td>
<td>9.388208 kg</td>
<td></td>
<td>for Plant - from usage of plant</td>
</tr>
<tr>
<td>Peelcoat kg Used per kg Aluminium</td>
<td>0.000175 kg</td>
<td></td>
<td>Crucible Coating</td>
</tr>
<tr>
<td>MgO 33-35%</td>
<td>0.000061 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C 14-16%</td>
<td>0.000028 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg 13-15%</td>
<td>0.000026 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si 11-13%</td>
<td>0.000023 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba 7-8%</td>
<td>0.000014 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Felpro kg Used per kg Aluminium</td>
<td>0.000063 kg</td>
<td></td>
<td>Ladle Coating</td>
</tr>
<tr>
<td>Shot used per kg of Al shipped</td>
<td>0.011204 kg</td>
<td></td>
<td>Finishing - Shotblasting</td>
</tr>
<tr>
<td>Ross Cone Fibre per kg Al Sold</td>
<td>0.000199 kg</td>
<td></td>
<td>Furnace - Metal transfer</td>
</tr>
<tr>
<td>Aluxal 100 - reverb furnaces - Flux per kg</td>
<td>0.000531 kg</td>
<td></td>
<td>Reverb Flux</td>
</tr>
<tr>
<td>Sodium Fluorosilicate 10%</td>
<td>0.000053 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium Carbonate &lt;5%</td>
<td>0.000027 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coverall 220 - Flux (kg per kg)</td>
<td>0.000443 kg</td>
<td></td>
<td>De-gassing Flux</td>
</tr>
<tr>
<td>Nitrogen (litres) per kg of Al</td>
<td>0.002647 litres</td>
<td></td>
<td>All Fluxing and De-gassing</td>
</tr>
<tr>
<td>Reverb Thermocouple Sheath Cl Weight per kg Al sold</td>
<td>0.000838 kg</td>
<td></td>
<td>Reverb Metal Holding and Melting</td>
</tr>
<tr>
<td>Scrap Furnace Refractory Weight per kg of Al sold</td>
<td>0.00109 kg</td>
<td></td>
<td>Scrap Melting Refractory</td>
</tr>
<tr>
<td>Hot Metal Furnace - Refractory weight per kg of hot</td>
<td>0.00072 kg</td>
<td></td>
<td>Hot Metal Delivery Furnace</td>
</tr>
<tr>
<td>Crucible - Cast Iron per kg of Al sold::</td>
<td>0.005817 kg</td>
<td></td>
<td>Crucible at Machine</td>
</tr>
<tr>
<td>Ladle - Cast Iron per kg of Al sold::</td>
<td>0.000997 kg</td>
<td></td>
<td>Ladle Transfer at Machine</td>
</tr>
<tr>
<td>Filter Mesh m2 per casting</td>
<td>0.000326 m3</td>
<td></td>
<td>Holding at machine Filter</td>
</tr>
<tr>
<td>Hydraulic Oil - Glycol per kg Al shipped</td>
<td>0.010589 litres</td>
<td></td>
<td>Hydraulic Systems</td>
</tr>
<tr>
<td>Propylene Glycol</td>
<td>0.003812 litres</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-3 : Cost-Usage model outputs for Casting AA to GaBi3v2 model
6.3.3.2 Graphical Output

*Figure 6-3: Graphical results from Cost-Usage model - electricity and natural gas usage*
As can be seen in Figure 6-3, the major users of electricity share in the total of the 4.209 MJ used in the manufacture of the Casting AA. The 6.831 MJ of natural gas which is used can also be seen of which the majority of it is used to remelt the scrap in the process. When looked at from the point of the functional unit, 5.171 MJ of electricity is used per kilogram of casting shipped and 8.391 MJ of natural gas per functional unit. This is a high number and is not representative of the process since the casting has a very low yield and this is considered by the author to be the biggest variable in the casting process with the biggest impact. This opinion was further reinforced with the second product which was analysed with the Cost-Usage model.

As would be expected the cost of electricity and natural gas resembles the use excepting the demand charge for electricity which is calculated according to the entire plant usage and also the power factor of this use. Natural gas is significantly cheaper to use per megajoule than is electricity.

The plant is located in Victoria, Australia, which uses brown coal to generate the base load electricity. Although other fuels are used in the generation of electricity and also the electricity in Victoria is connected to the national grid, the base load is all generated from the extremely inefficient burning of brown coal. This results in a full fuel cycle of 407.5 kilograms of CO₂ emitted for every megajoule of electricity used (source: Sustainable Energy Authority of Victoria) at the plant. The full fuel cycle of the natural gas is 54 kilograms of CO₂ emitted for every megajoule of electricity used (source: Sustainable Energy Authority of Victoria). This results in carbon dioxide emissions of 1.72 kg and 0.37 kg from electricity and natural gas respectively. Once again this is not representative of the process due to the yield of the Casting AA. A more detailed analysis of the electrical and natural gas cycles follows in the GaBi3v2 model with other emissions. The Cost-Usage model includes these emissions as they are easily recognised by industry and were simply included due to the availability of data.

From the graphical representation in figure 6-4, it can be seen that these two fuels result in differing amounts of the emission of carbon dioxide to the environment with electricity faring considerably worse. Also from this diagram can be seen that there is a close association between the carbon dioxide emission to the cost of the energy because of the electricity being a lot more expensive and a higher emitter of CO₂ per megajoule.
Figure 6-4: Graphical results from Cost-Usage model - CO₂ emissions and cost of energy for Casting AA.
6.3.4 Mass and Energy

As part of the check and balances, mass and energy were followed through the casting process to ensure that all of the mass and energy in the system was maintained. Table 6-4 shows the transfer of energy during the process of casting of the metal through its transformation from the molten state to a solidified casting.

<table>
<thead>
<tr>
<th>Item</th>
<th>Temperature (°C)</th>
<th>Temp Change (°C)</th>
<th>Energy change (MJ)</th>
<th>Energy to</th>
<th>Amount (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>From Shot Sleeve to Die</td>
<td>660</td>
<td>20</td>
<td>0.0384</td>
<td>Air</td>
<td>0.0192</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cooling water</td>
<td>0.0192</td>
</tr>
<tr>
<td>From Die to Casting Eject</td>
<td>350</td>
<td>310</td>
<td>1.3692</td>
<td>Die lube &amp; spray evaporation</td>
<td>0.2450</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Temp increase in waste water</td>
<td>0.1378</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Air</td>
<td>0.3423</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cooling water</td>
<td>0.7251</td>
</tr>
<tr>
<td>Casting Eject to Water Quench</td>
<td>70</td>
<td>280</td>
<td>0.5370</td>
<td>Cooling water</td>
<td>0.5370</td>
</tr>
<tr>
<td>After 1 Hour</td>
<td>20</td>
<td>50</td>
<td>0.0959</td>
<td>Air</td>
<td>0.0959</td>
</tr>
</tbody>
</table>

Table 6-4: Energy balance for casting process

From Table 6-4 it can be seen that of the original 2.0404 MJ the molten metal to be cast had prior to the casting process, 0.7024 MJ is transferred to air (including the evaporation), 0.1378 is transferred to the waste water and 1.2813 MJ is transferred to the 47 litres of cooling water that flows through the die during the interval of the cycle time of the machine (60 seconds) as the molten metal solidifies into the casting.

It is very difficult to fully account for all of the energy in the process because a lot is used / converted and almost none is recovered for other uses. In the example of Table 6-4, all of this energy eventually ends up as an emission to the air and none is recovered as a low grade heat for other purposes. Also the metal in the plant which arrives as molten metal has a residual energy which has not been included in the modelling. The GaBi3v2 software does not enable this to be taken into account and as such it has been greatly ignored for the purpose of this study.

Mass balances were conducted with regards to water consumption in order to assess where it was used in the process and where it went to as one of the aims of this study.
Mass balances are also required to determine other inputs and outputs from the process specifically with regard to the burning of fossil fuels in the plant.

Mass balances were conducted for each part of the process to ensure no mass was lost. The GaBi3v2 software helps in this regard by automatically calculating the mass and energy of all of the inputs and outputs to each process.

6.3.5 GaBi3v2 Plan

The process flow chart was transferred to the GaBi3v2 software and the main plan of the process to manufacture the Casting AA appears as figure 6-5. Added to this is the plan for the casting and trimming and for the supply of compressed air. Work was done in the area of the aluminium supply and this has been included in this report but the results are considered too unreliable to be included in this study but are interesting to add.

6.3.5.1 Production of Casting AA

Each box in Figure 6-5 represents one of the processes required to manufacture the Casting AA die casting. The box for casting and trim represents another plan because to add it to this plan makes the plan too complex to be easily understood. Also by making the main plan from smaller plans it becomes easier to change and add to the original. To make the main plan entirely from smaller plans was attempted but would not model properly.
Figure 6-5: GaBi3v2 created plan for the production of the Casting AA

From figure 6-5 can be seen the main areas of the plant such as melting and holding furnaces, cleaning and transfer of the metal, holding of the metal at the machine, casting and trimming and heat treatment. Ancillary processes such as the supply of natural gas and electricity are included in this main plan also where they are input into the process. The main output for the whole process is a one kilogram aluminium high pressure die casting part. Other outputs come from the individual components and are not shown on this plan.

Each individual box is represented by a screen as can be seen at Figure 6-5. This list of inputs and outputs for the remelt of the scrap shows the inputs of aluminium scrap, energy and the refractory materials used in the furnace. This information has all come from the Cost-Usage model. This process was repeated across the plan with the information from the Cost-Usage model being modified to work within the GaBi3v2 format.

From the Cost-Usage model, most of chemicals required did not exist in the GaBi3v2 database. More work is required to research these chemicals (such as those found in the flux) so they can be placed into the database and their effect known. For this study, if information could not be found about a chemical it was left out of the study. This has meant that a lot of the information from the Cost-Usage model was not able to be transferred across to the GaBi3v2 model.
6.3.5.2 Casting and Trimming

Due to the complexity of the process, a separate plan was made for the Casting and Trim process (Figure 6-7) as to include it in the main plan would have made it very difficult to appreciate where all of the flow connections were going. The Casting and Trim process has inputs from electricity, compressed air (another separate plan), machine and die maintenance, cooling water and also labour. It outputs the cooling water, waste water and the main output of one kilogram of die casting which can be seen in the main plan (Figure 6-5).
6.3.5.3 Compressed Air

The compressed air system is one of the biggest consumers of electricity in the plant. A separate plan was developed so it could be looked at in isolation to the rest of the plant. It has inputs of electricity and large amounts of cooling water, which is in a closed loop system. The output amount of air has been taken from other modelling to determine the energy usage per one Nm$^3$ of compressed air. All compressed air is vented to the atmosphere after use.
6.3.6 GaBi3v2 Results

6.3.6.1 GaBi3v2 Results - GWP 100

Figure 6-9: GaBi3v2 graphical output for GWP 100

Table 6-5: One kilogram of Casting AA emission of CO₂ to air

From Table 6-5 and the graphical display of the same information (Figure 6-9) it can be seen that the emission from one kilogram of casting will output 2.51kg of CO₂ eq to the atmosphere, with the majority coming from the electricity generation and the burning of natural gas. This is a result which is very comparable with that obtained from the Cost-Usage model. The graphical outputs from the models are not the same because it proved too difficult to set up the GaBi3v2 software for this result. Further levels can be
detailed from the GaBi3v2 software but this does not give any further useful information.

The table shows the majority of the emission is inorganic emissions to air which is essentially the CO$_2$ emission from the burning of the fossil fuels for energy.

### 6.3.6.2 GaBi3v2 Results - HTP

<table>
<thead>
<tr>
<th>One Kilogram of Casting AA HTP kg DCB Eq.</th>
<th>Total</th>
<th>Filtering / Cleaning and Transfer</th>
<th>Fork Truck 3.0 tonne capacity</th>
<th>LPG free refinery</th>
<th>Brown Coal Power Plant Natural Gas - Transmitted</th>
<th>Thermal energy from natural gas</th>
<th>Casting and Trim</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>0.4314</td>
<td>0.00014</td>
<td>4.63E-05</td>
<td>0.000608</td>
<td>0.0001089</td>
<td>0.0016894</td>
<td>0.2655</td>
</tr>
<tr>
<td><strong>Emissions to air</strong></td>
<td>0.43135</td>
<td>0.00014</td>
<td>4.63E-05</td>
<td>0.000608</td>
<td>0.0001089</td>
<td>0.0016894</td>
<td>0.2655</td>
</tr>
<tr>
<td><strong>Heavy metals to air</strong></td>
<td>0.42969</td>
<td>0.00014</td>
<td>4.66E-05</td>
<td>0.016313</td>
<td>3.97E-05</td>
<td>0.001267</td>
<td>0.26521</td>
</tr>
<tr>
<td><strong>Inorganic emissions to air</strong></td>
<td>0.0009601</td>
<td>0.00014</td>
<td>4.63E-05</td>
<td>9.99E-06</td>
<td>6.03E-05</td>
<td>0.0002453</td>
<td>0.000286</td>
</tr>
<tr>
<td><strong>Organic emissions to air (group VOC)</strong></td>
<td>0.0006963</td>
<td>0.00014</td>
<td>4.63E-05</td>
<td>1.48E-06</td>
<td>8.89E-06</td>
<td>0.0001322</td>
<td>2.41E-06</td>
</tr>
<tr>
<td><strong>Emissions to water</strong></td>
<td>4.51E-05</td>
<td>2.15E-07</td>
<td>5.67E-10</td>
<td>2.32E-09</td>
<td>4.49E-05</td>
<td>9.22E-10</td>
<td></td>
</tr>
<tr>
<td><strong>Analytical measures to water</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Heavy metals to water</strong></td>
<td>4.16E-05</td>
<td>2.15E-07</td>
<td>5.67E-10</td>
<td>2.12E-09</td>
<td>4.14E-05</td>
<td>9.22E-10</td>
<td></td>
</tr>
<tr>
<td><strong>Inorganic emissions to water</strong></td>
<td>3.40E-06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.40E-06</td>
<td></td>
</tr>
<tr>
<td><strong>Organic emissions to water</strong></td>
<td>3.50E-08</td>
<td>1.72E-11</td>
<td>1.12E-14</td>
<td>2.00E-10</td>
<td>3.48E-08</td>
<td>1.82E-14</td>
<td></td>
</tr>
</tbody>
</table>

**Table 6-6 : One Kilogram of Casting AA - HTP kg DCB eq**

Human Toxicity Potential (HTP) is measured in Dichlorobenzene (DCB) equivalent. From the Table 6-6 it can be seen that the major contribution to HTP is made by the Brown Coal Power Plant and Casting and Trim. The high figure for Casting and Trim is due to the high electricity consumption from this process and the other process linked to it in the model. Further depth of these results shows that the electricity is responsible for over 99% of this emission for the process of high pressure aluminium die casting.
6.3.6.3 GaBi3v2 Results - Mass

Figure 6-10: GaBi3v2 graphical input by mass

Figure 6-11: GaBi3v2 graphical output by mass
The total amount of material used to make one kilogram of Casting AA die casting is 20.55 kilograms which also includes all energy. The mass is made up of mostly water since water is used in the die casting process and in the generation of the electricity.

Figure 6-10 shows the inputs and Figure 6-11 shows the outputs. The scales on the figures are different but the masses do equate. Space does not allow the tables for mass of the inputs and outputs to be inserted here but they can be found in the Appendix B.

### 6.3.6.4 GaBi3v2 Results - All

<table>
<thead>
<tr>
<th>Equivalency Name</th>
<th>Quantity</th>
<th>Unit</th>
<th>Largest Contributor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acidification potential (AP)</td>
<td>0.0037788</td>
<td>kg SO₂ Eq.</td>
<td>Forklifts</td>
</tr>
<tr>
<td>Aquatic ecotoxicity potential (AETP)</td>
<td>0.0011154</td>
<td>kg DCB Eq.</td>
<td>Thermal energy from Natural Gas</td>
</tr>
<tr>
<td>Carcinogenic substances (EI 95)</td>
<td>4.4858 E-07</td>
<td>kg PAH Eq.</td>
<td>Transmitted Natural Gas</td>
</tr>
<tr>
<td>Eutrification potential (EP)</td>
<td>0.00062431</td>
<td>kg Phosphate Eq.</td>
<td>Forklifts</td>
</tr>
<tr>
<td>Global warming potential 100 Years (GWP100)</td>
<td>2.4944</td>
<td>kg CO₂ Eq.</td>
<td>Casting (Electricity)</td>
</tr>
<tr>
<td>Global warming potential 20 Years (GWP20)</td>
<td>2.5997</td>
<td>kg CO₂ Eq.</td>
<td>Casting (Electricity)</td>
</tr>
<tr>
<td>Global warming potential 500 Years (GWP500)</td>
<td>2.4469</td>
<td>kg CO₂ Eq.</td>
<td>Casting (Electricity)</td>
</tr>
<tr>
<td>Heavy metals (EI 95)</td>
<td>5.2261 E-07</td>
<td>kg Pb Eq.</td>
<td>Thermal energy from Natural Gas</td>
</tr>
<tr>
<td>Human toxicity potential (HTP)</td>
<td>0.43145</td>
<td>kg DCB Eq.</td>
<td>Casting (Electricity)</td>
</tr>
<tr>
<td>Ozone depletion potential (ODP, catalytic)</td>
<td>5.3802 E-09</td>
<td>kg R11 Eq.</td>
<td>Thermal energy from Natural Gas</td>
</tr>
<tr>
<td>Photochemical oxidant potential (POCP)</td>
<td>0.011596</td>
<td>kg Ethene Eq.</td>
<td>Casting (Electricity)</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity potential (TETP)</td>
<td>1.0048</td>
<td>kg DCB Eq.</td>
<td>Thermal energy from Natural Gas</td>
</tr>
</tbody>
</table>

Table 6-7: Table of results from GaBi3v2 software

Table 6-7 displays all of the different results available from GaBi3v2. From these results the full LCA can be performed by weighting these numbers or normalising the results. This has not been done as part of this study for reasons outlined in Chapter 7.
6.4 Casting BB

6.4.1 Description of Product

The Casting BB is an automotive manual transmission case. It is cast in a 1250 tonne casting machine in a single cavity die. It has a shipped weight of 7.28 kilograms and the runner, biscuit and overflows weigh 2.95 kilograms giving a total shot weight of 10.23 kilograms. The yield of the casting is 71.16 percent.

After casting the Casting BB is trimmed, fettled, broached and leak tested before being packed. In 2001, 73,500 castings were produced of which 4.76 percent (3,500) were rejects.

The variables for the Casting BB (see Table 6-8) were entered into the Cost-Usage model. The following step of using the GaBi3v2 model was not taken because the differences between the two results from the Cost-Usage model illustrated the point of modelling the second casting.

Figure 6-12: Casting BB
### 6.4.2 Input Variables Casting BB

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage Uptime</td>
<td>75%</td>
</tr>
<tr>
<td>Number of Cavities in Die</td>
<td>1</td>
</tr>
<tr>
<td>Cycle Time of Machine (sec)</td>
<td>90</td>
</tr>
<tr>
<td>Shipped Weight (kg)</td>
<td>7.28 kg</td>
</tr>
<tr>
<td>Biscuit and Runner (kg)</td>
<td>2.5 kg</td>
</tr>
<tr>
<td>Shot Sleeve Diameter (mm)</td>
<td>118 mm</td>
</tr>
<tr>
<td>Standard Biscuit Length (mm)</td>
<td>40 mm</td>
</tr>
<tr>
<td>Average Biscuit Length (mm)</td>
<td>40 mm</td>
</tr>
<tr>
<td>Overflow Weight (kg)</td>
<td>0.45 kg</td>
</tr>
<tr>
<td>Good Castings Produced 2001</td>
<td>70000</td>
</tr>
<tr>
<td>Reject Castings Produced 2001</td>
<td>3500</td>
</tr>
<tr>
<td>Actual Weight of casting</td>
<td>7.280 kg</td>
</tr>
<tr>
<td>Labour No. of Machines Supervised</td>
<td>4</td>
</tr>
<tr>
<td>No. of Toolmakers per machine</td>
<td>1.07</td>
</tr>
<tr>
<td>Labour Time to Validate 1 Casting (min)</td>
<td>45 min</td>
</tr>
<tr>
<td>Castings validated per 24 hour period</td>
<td>1</td>
</tr>
<tr>
<td>Bolster Expected Life (shots)</td>
<td>1000000</td>
</tr>
<tr>
<td>Weight of bolster (both halves) (kg)</td>
<td>15,500 kg</td>
</tr>
<tr>
<td>Insert Expected Life (shots)</td>
<td>200000</td>
</tr>
<tr>
<td>Weight of one pair of inserts (kg)</td>
<td>1,317 kg</td>
</tr>
<tr>
<td>Die Lube Ratio (water:die lube)</td>
<td>70 :1</td>
</tr>
<tr>
<td>Flow Rate / Lube Spray Nozzle (lt/min)</td>
<td>6 lt/min</td>
</tr>
<tr>
<td>No. of Water Spray Nozzles</td>
<td>22</td>
</tr>
<tr>
<td>No. of Lubricant Spray Nozzles</td>
<td>21</td>
</tr>
<tr>
<td>Die Lube Spray Time (sec)</td>
<td>4 sec</td>
</tr>
<tr>
<td>Water Spray Time (sec)</td>
<td>4 sec</td>
</tr>
<tr>
<td>Tip Lube Amount per Shot (litres)</td>
<td>0.003</td>
</tr>
<tr>
<td>Shot Sleeve Shots bw reconditioning</td>
<td>40000 shots</td>
</tr>
<tr>
<td>Max. no. of Reconditionings / sleeve</td>
<td>2</td>
</tr>
<tr>
<td>Weight of Shot Sleeve (kg)</td>
<td>70 kg</td>
</tr>
<tr>
<td>Plunger Tip Shots bw reconditioning</td>
<td>100000</td>
</tr>
<tr>
<td>Labour time of Reconditionings (min)</td>
<td>15 min</td>
</tr>
<tr>
<td>Max. no. of Reconditionings per tip</td>
<td>5</td>
</tr>
<tr>
<td>Weight of Copper Tip (kg)</td>
<td>7.42 kg</td>
</tr>
</tbody>
</table>

**Table 6-8 : Casting BB input variables**
6.5 Comparison Casting AA Vs Casting BB

<table>
<thead>
<tr>
<th>Major Differences Casting AA Vs Casting BB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting shipped weight (kg)</td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>Shot weight (kg)</td>
</tr>
<tr>
<td>Yield</td>
</tr>
<tr>
<td>Number of cavities</td>
</tr>
<tr>
<td>Casting machine size</td>
</tr>
<tr>
<td>Number of components manufactured per year</td>
</tr>
<tr>
<td>Reject rate</td>
</tr>
<tr>
<td>Cycle Time of Machine</td>
</tr>
</tbody>
</table>

Table 6-9: Major difference between Casting AA and Casting BB

<table>
<thead>
<tr>
<th>Summary of Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting AA</td>
</tr>
<tr>
<td>Electricity used per casting</td>
</tr>
<tr>
<td>Electricity used per kg of casting shipped</td>
</tr>
<tr>
<td>Natural gas used per casting</td>
</tr>
<tr>
<td>Natural gas used per kg of casting shipped</td>
</tr>
<tr>
<td>Total energy used per casting</td>
</tr>
<tr>
<td>Total energy used per kg of casting shipped</td>
</tr>
<tr>
<td>Total CO₂ emitted per casting</td>
</tr>
<tr>
<td>CO₂ emitted used per kg of casting shipped</td>
</tr>
</tbody>
</table>

Table 6-10: Summary of results - Casting AA and Casting BB

Table 6-10 and Table 6-11 give a generalisation of the results for a comparison between the two different castings, Casting AA and Casting BB. The evidence suggests that basing a study on one casting will give incorrect outcomes if the results from one study are used to generalise the whole process. The reasons for this wide range of results can be traced back to the slight variations in the process and to some of the key variables which became clear when the sensitivity of these variables was investigated.
### Table 6-11 - Results Casting AA and Casting BB

Table 6-11 shows that in every output from the Cost-Usage model, The Casting BB uses less of all materials and resources and has lower emissions than the Casting AA on a per kilogram of die cast product basis. The Casting BB has the higher weight and the higher yield. The evidence suggests that these two variables alone are the key variables when determining the results from modelling any high pressure die casting.
6.6 Sensitivity

The results shown previously indicate that the weight of the casting is one of the key variables in the casting process when determining the outputs and resource usage of the process. This is based on the higher weight casting being better matched to the die casting machine and therefore using all of the resources more efficiently. The higher weight of Casting BB is matched by the substantially better yield. To test this hypothesis further requires more castings to be modelled and this does constitute further work in this area of study.

One of the key variables was considered to be the yield of the casting. With any die casting manufactured with the high pressure process, it becomes more difficult to maintain a high yield if the casting shipped weight is low. This is because of the requirement for a biscuit to be used to transfer the hydraulic pressure from the machine into the solidifying casting. The biscuit is usually a large percentage of the runner system by weight and is dependant on the diameter of the shot sleeve and the accuracy of the ladle. An inaccurate ladle will deliver too much or too little metal to the casting machine. Too much metal results in an inefficient process due to the extra metal used (decreasing the yield) but too little metal will often result in a reject casting which further exacerbates the problem of inefficiency. As can be seen from the results for these two very different castings, an increase in the yield of the casting will reduce the energy required and thus the CO₂ emitted (see Figure 6-13).

These two figures show similar curves since the results were derived using the same model. Further work should investigate the relationship here but it can clearly be seen that to increase the yield of any casting will decrease the emission of CO₂ to the atmosphere. Looking back at Figure 6-4, the explanation becomes clearer due to the large emission (approximately 10% for the Casting AA) of CO₂ for the remelt of scrap. The curves can be seen to move toward a base emission of CO₂ depending on the yield of the casting. This will change due to the different subtleties of the casting processes used by each casting and the amounts of energy used by different finishing processes. For example the Casting AA is heat treated and the Casting BB is not. The energy used in heat treatment is not dependant on the yield of the casting since it is only the casting itself which is heat treated. This will mean that there will always be a base load of energy used no matter what the efficiency.
Further sensitivity analysis showed that any variable that increased energy usage, predictably increased emissions from the process. This also held true for decreasing any efficiencies in the process which also add to the emissions. Resource depletion (such as materials and water but excluding energy) was generally tied to efficiencies in the process such as reject rate, since a reject made must be remanufactured using all of the materials and resources.

Figure 6-13: Yield Vs CO$_2$ emission for Casting AA and Casting BB
7 Discussion

7.1 Outline of Chapter

The Discussion chapter follows through the points of the study that have eventuated from the previous chapters. The LCA tool is discussed in its methodologies and applicability to aluminium die casting. The Cost-Usage model developed with this study is discussed with the GaBi3v2 model including improvements which can be made to each. Data is discussed in length as it forms such a large part of this and any other LCA study. The value of the study is presented with the outputs and suggested improvements to the process. Further work is presented followed by the conclusion to the study.

7.1.1 Confidentiality of Data and Information

This study was conducted in a commercial die casting plant and as part of this, real data was used to validate the models. Due to the nature of this data, it has been agreed not to publish any of the cost structure of the plant and as such this data has been removed from the results and substitutions made in the model as found in Appendix C. This information was seen by plant management to be too critical to the business to be released in any form and the author respects their wishes. This data, together with a complete model, has been given back to the plant for their use.

7.2 LCA Methodology

The LCA methodology is well suited to this process and can give useful information about the process but the results from the study should not be considered in isolation. The methodology has many different aspects that can be changed and manipulated to alter the results, either intentionally or inadvertently. The results from any LCA need to be looked at closely to determine items such as data quality and the system boundary.

7.2.1.1 System Boundary

The system boundary can be changed to manipulate the findings of the study. Whether transport is included in the assessment will have a large affect on the results. Also, does the study include the raw material and to what level of manufacture? Is transport included in the manufacture of the raw materials? This list is endless but it is imperative that the system boundary be clearly stated for all to see.

Also to be neglected (but as noted) is the aluminium itself. Secondary aluminium as used at the site requires only 5 percent of the energy that is required to produce aluminium from bauxite. This is significant since 1% of all CO\textsubscript{2} emissions in the US (Lupis 1999) are from primary aluminium production. Another significant energy saver is that the site receives 87 percent of all its aluminium from the supplier in molten form.
This saves the energy of melting the metal and also eliminates the waste from the process of making ingots.

By simply moving the system boundary for the study the results can be drastically altered. From the results it can be clearly seen that a large amount of the GHG emissions occurs off-site at the power generation site. If the system boundary does not include this then the results will dramatically change.

Transport of materials to and from the plant. Distribution losses from the electricity and the natural gas. These decisions are made at the beginning of the study and may or may not affect the outcomes depending on factors such as distances travelled and method of transportation.

7.2.1.2 Weighting

Weighting is the term used in LCA where one impact is given greater importance than another. This is usually done relative to the aims of the study but is not used in the ISO standards for LCA. Weighting has not been used in this study because of a commonly held belief that it is too subjective and can be used to give whatever results are desired. It was considered that the raw data is more useful to this study and has thus been preserved. Further work in this area could use this raw data and apply weights to it but it does not serve any purpose for this study.

7.2.1.3 Normalisation

Normalisation is a far more useful tool in that it takes the unweighted results and compares them to national or regional data. For example a number of grams of heavy metals may be released to the atmosphere by a process. By comparing this release with the total amount of this heavy metal released to the atmosphere for the country (with data from a national database), it can be seen how much this process contributes to the overall problem.

This presents two problems when related to this study. The normalisation methodology is often applied to European countries where the density of population is much higher than Australia. Any data relating to even an Australian state is often dealing with a land size larger than most European countries with a much lower population density. This gives a distorted picture. The next problem is more fundamental. Very little data exists for Australia to normalise the study against. Normalisation data is location and time sensitive and does not exist for Australia, let alone the more useful state or regional data. Where it does exist it is not complete and this also gives a distorted picture. Thus, normalisation has also not been used in this study as it is felt that the results would not be accurate and therefore not of any use. The raw data has been maintained so that at a later date when more data is available, normalisation could be done as part of further study.
7.2.1.4 LCA Design Planning

LCA is a useful tool for studying existing products and processes, since following the detailed study, improvements can be made. To realise the full effectiveness of LCA it should be used by designers and engineers in the planning phase of a product or process. This study has found many improvements which can be made to the plant and this is good. The fact that these inefficiencies have been in the plant for close to 20 years and the outputs from the process can be multiplied by over 100,000 tonnes of cast aluminium product suggests that the real savings could be made before a plant or a new process is set up. By studying the process in the planning phase gives the biggest benefit of LCA.

7.3 LCA Applicability to Aluminium HPDC

The LCA process was successfully used with the aluminium HPDC process and it is the recommendation of this study that it should be used more often (in the planning phase) for die cast components. The LCA methodology could also be successfully applied to any die casting process using any material. This is not a surprise since the methodology has been successfully applied to many other processes and products.

LCA on the aluminium HPDC process will give general answers which should not be applied to individual products manufactured by that process unless careful consideration is given. From the results it can be seen that for different cast components manufactured in the same plant, very different results were found. The range in the results is due to the following factors that have a heavy influence on the results from the aluminium die casting process on the individual product.

7.3.1 Variations in the HPDC process:

There are over 200 process variables in any HPDC process. Variations in any of these can mean the difference between a good casting and a reject. Most of these variables exist at the micro level of the process. The variations in the process which change the results of this study are more on the macro level of the process and have little if any affect on whether a good part or a reject is made. This makes improvements easier to implement and also removes one of the biggest barriers to change in any die casting plant. That is to change anything that may affect quality. As the variations in the process (for good and bad) will not generally affect quality they can be manipulated to find the optimum process that has the least environmental load and cost.

7.3.1.1 Yield

The results show that yield (the shipped weight of the component divided by the shot weight expressed as a percentage) is the single most important factor when comparing two die cast components. If the shipped weight of the casting and the yield are not within 5 percent then the comparison will not be meaningful. This is because most of the gas used in the process is in the shot weight and the subsequent remelt of the
scrap. A lot of the electricity is used at the casting machine and this also comes back to the shot weight. If the shot weight varies too much, the components probably should not be cast in the same size machine. This introduces the variable of the casting being made on the right size machine.

The following is an example of how the yield has an effect throughout the casting process. The original metal is beyond the system boundary as is the transport to the site, so will not be considered but the metal used for the shot weight must either be remelted from ingot or held as molten metal. Emissions from the furnaces would be reduced with a better yield giving less metal initially. A higher yield would mean less work for the furnace operators and fork drivers delivering the metal to the machines (i.e. more shots for each ladle of metal delivered). Less flux and nitrogen would be used to clean the metal. If the quantity of initial metal were lower, less heat would be required to be removed from the casting for solidification thus potentially reducing the cycle time of the machine. Removing less heat would require less cooling water and less sprayed cooling water, helping to preserve this precious resource. Then the lower amount of scrap would mean that the scrap bin would be emptied less often, saving labour and forklift resources. The less scrap being melted the less natural gas is used to melt it and less dross is lost from the process. All of this does have a substantial benefit in terms of emissions and also a great benefit in terms of cost.

When considering the yield, the actual weight of the casting also should be taken into account. The CU model allows for this variable but it will change from one casting to the next. The plant uses a shipped weight that the casting is supposed to weigh but due to various production factors such as die wear and flashing, the actual casting weight when measured varied from the shipped weight by as much as 4 percent from random samples measured. This has large economic considerations but also can change the yield of the casting and as such this should be taken in consideration.

### 7.3.1.2 Size of HPDC Machine

An assumption is made in the production of these castings that they are being made on the machine that correctly matches the casting size (shot weight, projected area, metal pressure, et cetera.). If this is not the case, either the machine is too big or too small, inefficiencies will appear in the process (The CU model will pick these up if a number of different castings are modelled and the results benchmarked). If the machine was too small, excessive rejects will be made with porosity problems resulting from the machines inability to keep the die closed during the shot. This is a simple calculation of metal pressure multiplied by casting projected area. This will also result in the die flashing causing the casting to be too thick and metal being given away to the customer. This will directly affect the bottom line. If the casting is being made on a machine that is too big the energy required to run the bigger machine will result in inefficiencies also. Although rejects and casting wall thickness losses could be reduced resulting in an overall gain. Capital costs of larger machines and also lost opportunity costs (bigger castings usually mean larger profit margins) also need to be considered.
Thus, when comparing two castings, care needs to be taken to ensure that the two castings are being made on not only the same machine but that the machine is correctly sized for both so as not to introduce further errors. This is rarely the case for two different castings.

With most casting plants, the casting and machine will be closely matched with the projected area being adjusted by the number of overflows, runner size, vent size and also the number of cavities. But it is usually spare production capacity that will determine in which machine a casting is to be manufactured.

### 7.3.1.3 Aluminium Supply – Molten versus Ingot

The plant under study received most of its aluminium in molten form. This saves a considerable amount of energy off-site in the fact that energy is not lost in the making and solidification of the aluminium ingots. It also saves the energy of remelting the ingot in the plant which is one of the most energy intensive processes. The offset of this is the use of some energy to preheat the crucibles used to transfer the molten metal from the supplier to the plant but this is minor in comparison to melting the ingot in the plant (approximately 1 MJ per tonne of aluminium). Considerable labour savings are achieved though not handling the ingot in the plant also. If the molten metal delivery was to fail, then this would add to the cost as well as the environmental load. This is something which becomes more important for smaller plants which do not use enough metal to justify the molten metal deliveries.

This variable was included in the modelling and a small increase in emissions from the increased use of natural gas was found when a larger percentage of the aluminium in the plant was received as ingot. This has large flow on effects that were not included in the study of the need to operate more melting furnaces and the increase in labour required to operate these furnaces.

### 7.3.1.4 Furnace Type and Efficiency

The furnace type and subsequent efficiency of that furnace which is used for both melting and holding will have a great effect on the cost and emissions of the component. The site under study used natural gas fired wet-bath reverberatory furnaces for scrap melting and molten metal holding and used gas fired open top crucible furnaces for holding at the die casting machine. These types of furnace are not the most efficient types available and are in the plant on the basis of economics only. Functionally they perform their purpose and are generally reliable. At the current cost of energy into the plant, there is no benefit to replacing them. These furnaces are at best 35 percent efficient if in perfect condition. With wear and tear, refractory damage and burners out of tune, this efficiency can drop to be as low as 10 - 15 percent if all of the mentioned factors are out of favour.

The results indicate a relative efficiency for the metal melting furnaces at 25 percent. By changing the types of furnaces used in the plant (or comparing with another plant)
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the results will vary considerably by the type and condition of the furnaces used for both metal melting and metal holding.

7.3.1.5 Die spray

Different castings require different amounts of die spray. Some castings may require a different type of die spray (sometimes called anti-solder) in addition or instead of the original die spray. The spray amount will usually be in proportion to the surface area of the die but will also change according to the draft angles of the die and features such as ribs (also known as lighteners) and holes (made by core pins in the die). These will all change the amount of die lubricant sprayed on the die surface and will change from casting to casting. This variable is set up by the die casting engineer but could also be changed on the same casting from run to run or even during a run when problems such as soldering occur.

7.3.1.6 Water spray

Water spray is used in many die casting plants to cool the surface of the die prior to die spraying. This is required because the die lubricant will only adhere to the die surface if it is in between a range of temperatures (generally 180°C and 250°C but this will vary for different die lubricants). As the casting is released from the die, the die surface will be at differing temperatures according to features of the casting (wall thicknesses of the casting will determine how much heat is required to be removed for solidification of the metal to occur) and also features of the die (internal water cooling channels and their location relevant to features of the casting). All of these variables will change the amount of water (if any) required to be sprayed on to the die surface.

7.3.1.7 Finishing Processes

The finishing processes used will vary from casting to casting. In this study, heat treatment was used on one of the castings to relieve stresses introduced from the shotblasting and casting processes. The shotblasting is used to remove any loose material from the casting after trimming and fettling and to give the casting a uniform finish. The trimming and fettling is required to remove runners and overflows from the casting and also remove any sharp edges from the casting. The heat treatment process is energy intensive and if not required (this is the case for most castings) the energy consumed in the manufacture will be considerably less. The results predictably indicate that the more finishing processes that are used, the higher the consumption of materials and energy. This leads to higher emissions and waste from the manufacture of the component.

7.3.1.8 Labour

Due to the many variations of finishing processes used in die casting, and the labour efficiency of the plant and die casting cell, labour will vary for differing castings produced within a given plant. It is also the experience of the author that labour will vary considerably from plant to plant and this must be taken into account. This does not
affect the environmental consequences of the casting very much but it has a major
effect on the cost of a casting as labour can form a large part of the cost of the
component (these results are not available due to confidentiality).

7.3.1.9 Energy Supply

This study has considered the energy as supplied in the state of Victoria. This means
natural gas supplied from the Bass Strait fields and base load electricity supplied from
brown coal generation. The electricity is possibly the worst type of generation
anywhere in the world for efficiency and for pollutants (excluding nuclear which has a
different sub-set of problems). This can have a very great affect on the outcomes of the
study. From the results it is seen that it is the consumption of energy that is the largest
output of nearly all of the major pollutants. If the plant under study were located in an
area which used all hydro generated electricity and did not use natural gas, the
emissions would be significantly lower. The source of the energy would change the
outcome of the study and this must be considered when looking at the results from this
type of study.

7.4 Cost – Usage Model

As part of this study, a comprehensive cost and usage model has been developed.
This model was developed to firstly store all of the collected data from the plant. It was
then used to cross-reference the data to be able to get actual usage of the main
materials. From here the model was developed so as the amounts of each material
used for each casting could be determined. Information about the ingredients and cost
of each input were captured and this information then gives an output of both the cost
of the materials used and quantity of the materials used which can then be entered into
LCA software for further assessment.

The Cost-Usage (CU) model has been developed and tested in a die casting plant. It
can be adapted to other die casting processes such as Low Pressure Die Casting
(LPDC) and Gravity Die Casting (GDC). It can also be adapted to suit other metals
such as zinc or magnesium. The CU model is accurate for the process studied (HPDC)
and is useful to locate improvements to the process both in terms of cost and
environment.

The results from the model cannot be fully disclosed due to confidentiality but the CU
model can be found in Appendix C.

7.4.1.1 Activity Based Costing

It was decided that to gain an accurate picture of the quantities of each input which
were used to make each casting, an activity based method should be used. This
involved choosing a die cast component and then capturing the actual amounts of each
input used at each stage of the process. This entailed either measurement where
possible, or estimation based on knowledge of those using the process where
measurement was not possible or practical. The more common way these inputs are usually measured and costed in a plant is to look at how much is used for a year and dividing this by the amount of aluminium sold in the plant for the year. This gives a good estimation but was not considered accurate enough for this type of study. In some areas of this study it has been used where no other method is reliable enough to be used and this must be remembered when looking at some of the results. The activity based method gives very accurate information but must be considered for each individual casting. In most plants, where the number of different castings can number into the hundreds, this can be a time consuming process. Further cost-benefit analysis would be required to determine if this would be beneficial to do across an entire plant.

7.4.1.2 Model Complexity

The cost-usage model is extremely complex. In involves the entering of over 200 variables into the model. The complexity of the model could be reduced for simplicity but this would reduce its accuracy. Similarly, the complexity could be increased and this would need to happen if it were to be used in a plant on a day to day basis. This is because the model does not adequately address items such as capital expenditure, depreciation and fixed overheads. These would be relatively easy to place into the model but were not required for this study as capital equipment has not been considered and fixed overheads have been greatly ignored for their environmental contribution. The model follows each part of the process and as such the level of complexity would need to be determined by the end user. In its current form, it would require only basic training to be able to use the model but any modifications to its internal calculations are not recommended without advanced familiarity with the model.

This model has been developed specifically for high pressure die casting of aluminium but could be altered to suit other casting processes with other materials. Further development of the model could continue into its use with magnesium, as this is a high growth area of the industry. Also further work could make the model suitable for use with gravity casting, low pressure casting or sand casting. The model has been created with this in mind so major modifications would not be necessary to meet this aim.

7.5 GaBi3v2 Software

The GaBi3v2 software is good for process modelling, as was undertaken for this study. It was however barely adequate in a number of areas which made its usefulness limited. A high trained expert in the software could easily access more of the potential of this package as it has a lot of features that would be useful if access to them was easier.

7.5.1.1 Inadequate Databases

As mentioned earlier, the database, which was purchased as part of the GaBi3v2 software, was incomplete and held only a bare minimum of information on the materials promised. Of the materials required for the die casting process, less than 10 percent
were available. Although this was not completely unexpected, some of the major materials that were present in the database did not contain any more information than a name. Development of this database into a more usable form would be another project itself. Where possible and the data were available, it was added to the database but overall there was a general lack of data.

### 7.5.1.2 Difficult to Understand

The software itself, although flowing logically, is difficult to understand at times mainly because it offers only a limited help file and does not explain in plain English. This is thought to be a function of the translation from German to English. Many of the formula functions have not been translated from German but these were not used in this study so was not a hindrance but removed one of the possible benefits of the database provided with the software.

### 7.5.1.3 Errors in German

Many of the errors that come up from time to time in the program, have not been translated to English and are still in German. This proved frustrating when no help is provided in the manual and help has to be sought from the providers of the software. Although this was rare it happened more than once.

### 7.5.1.4 Inadequate Manual

The manual gives only a rough description of what is contained in the software and gives only a few clues as to how to use the software. This proved to be of limited use in the study.

### 7.5.2 Software Improvement

Areas for improvement in the software

- Improve translations in the software, the database and the errors.
- Improve the manual as provided with the software with better explanations of how to use the software, what the errors mean and how to fix them (troubleshooting).
- Increase the information on the existing materials in the database.

### 7.5.3 Software summary

This software is quite powerful and with the right resources to further develop the database, it would become very useful. Unfortunately this required a highly trained person who has experience and is familiar with the software to gain the most benefits
from it. Time did not allow this to be gained from this study but with further work this software could be used as a powerful tool in this area of study and also LCA.

7.6 Data

Data is a very large issue in the Life Cycle Assessment methodology. It becomes an even larger issue when the study is considering an area of manufacture not previously considered for study in LCA. This has been found to be the case with this study and there are a number of reasons and explanations for gaps and holes which have been unable to be filled during this study. Data can be difficult to find and there is also a large cost associated with a lot of this data when it can be found. Other problems include aggregated data, incomplete data, unreliable data and out of date data.

7.6.1.1 Supplied Databases by GaBi3v2

For the LCA collection and storage of acquired data, the GaBi3v2 software package was purchased including the database. The intention was to purchase as complete a database as possible so as searching for related data would not be required. The sales pitch was good and the demonstration program was also good but when it comes to value, an empty database was purchased. A lot of the items are in the database but the fields are not filled in. This was apparently due to a misinterpretation or misunderstanding. Either way it means that a lot of estimating has gone on and another year of work would be required to fill in the fields in this database to bring the results from this part of the study up to an acceptable level.

7.6.1.2 Aggregated Data

When data is supplied from other studies it is usually in an aggregated form. This means that the data comes in a bundle and no information about the data in known. For example the data for a process to make steel sheet has data on inputs and outputs but no information on the different parts of the process such as what type of electricity was used, or the size of the rolling mill. This information becomes important when localising this data and making substitutions for the local environment. If the information is not provided about the data, localising the data becomes difficult and adds further inaccuracy to the study. For these reasons disaggregated data is preferred where all of the information about the data is known and substitutions can be made without creating inaccuracy. Unfortunately the groups who create the disaggregated data think it has a high value and thus change accordingly for it. This makes it difficult to obtain and as such aggregated is used often and estimations made and noted.

7.6.1.3 RMIT Data

The Centre for Design at RMIT University have completed many studies in LCA and where the work has not been sponsored by an outside party the data has been made available free in the public domain. This data includes information about Victorian energy supplies of electricity and natural gas in a disaggregated form. This data was
particularly invaluable for this study as Victorian electricity in particular is generated in a
different way to most of the world. Brown coal is possibly the most inefficient and most
polluting (depending on how nuclear energy is viewed) method of generating electricity.
Victoria’s base load electricity is generated by this method. Data on the collection and
distribution of natural gas was also made available. The size of these databases is very
large and is incompatible with the chosen software so all of this information has been
placed in the GaBi3v2 database manually. Many other organisations offer to sell this
type of data for thousands of dollars. Without this help, this data would have been
estimated. This would have placed a large error in the study since the data as supplied
in the GaBi3v2 database was completely different to the data from RMIT University.

7.6.1.4 Country Specific Data

Data is collected as country specific. This is listed in any database with the country
where the data was collected and will vary from country to country due to changing
environments, laws and technologies. This makes it difficult as virtually no data exists
for Australia and where it does, it is not region or state specific. This is important
because things such as electricity generation vary widely across this country with very
high GHG emissions in Victoria with brown coal generation to almost zero GHG
emissions in Tasmania with hydro power generation. Once again this results in
estimations as all of the data is aggregated and substitution is difficult. Placing more
inaccuracy in the study.

7.6.1.5 Process Specific Data

When data is presented in an aggregated form the process used in the creation of this
data will be mostly unknown. What technology has been used, what manufacturing
practices are used and other information about the manufacturing process are left out
of the data. This makes an estimation necessary that the data required will closely
match the process which is actually used to make the material required. This becomes
more of a problem when a manufacturer will usually not share information about their
process in the interests of confidentiality.

As part of this study, many of the manufacturers were approached to discover more
about the products which were supplied into the plant. Only one (the aluminium
supplier) gave a positive result with most not even replying to letters. Where replies
were forthcoming, no information was offered. Thus a lot of this data was estimated
from information required by law to be given to the plant. This introduces a large error
to the study also.

7.6.1.6 Time Specific Data

This study was conducted on actual data from a plant for the year 2001. Much of the
data used in the database is for earlier years with some been up to 15 years old. It is
difficult to know anything about this data for the reasons outlined previously and as
such it is mostly taken on face value which is probably different from the actual
processes used to make the materials today. Thus, more inaccuracy was introduced into the process.

7.6.1.7 Data Manipulation

From all of this information it can be seen that data can be manipulated and justified to suit almost any answer that is required by the sponsor of the study. As most LCA work is sponsored by private companies, much of the real data can be hidden and changed to suit a required result.

7.6.1.8 Data Formatting

Although a standard now exists for LCA data storage (ISO 14048) it has only recently been developed and is still not widely used. Many of the software platforms are not using the standard including the software used for this study. This results in many inconsistencies with any available data, not so much in the accuracy of the data but how much information it contains. Different ways of representing chemicals names (full names versus symbols and formulas), places of emissions (land or sea) and number representation (scientific or standard). This results in any data that is stored in one software format not being compatible with any other software format. All data is required to be manually re-entered which is time consuming and inefficient. This will change as software creators begin to adopt the standard but this will not be any benefit to old data and will result in old data being required to be manually transferred or lost.

7.6.1.9 Variations in the Collected Data

As this study uses actual data that has been collected in the plant, variations will naturally occur causing inaccuracies in the study. Data was collected in the areas of actual stores usage, natural gas usage, electricity usage, water usage, waste water, scrap steel, dross reclamation, etcetera. While some of these are clearly absolute values, some were estimated to a degree. For example, in the collection of natural gas usage for the reverberation furnaces there is no accurate way of measuring how much metal goes into the furnaces. Generally the amount charged is known to an accuracy of 10% on a 500 kilogram scrap bin but weighing each charge prior to the furnace is not feasible and as such an estimation method is used. To make sure that this did not become a large source of error, a lot of data was collected over a number of weeks to reduce this error. There still exists an error but through averaging the incoming charge and then the outgoing metal this has been reduced as much as possible. There is also an assumption that the metering on the furnaces is accurate although the meters are calibrated from time to time so this is assumed to be accurate. Electricity data was gathered over a period of time and once again averaged, although this is not thought to introduce errors as the equipment was calibrated prior to the study and the one meter was used for the gathering of all data.

The equipment used to gather the electrical data was a data logging electrical meter which measured and logged relevant electrical data (volts, current, power and kVA across all three phases) and could be easily connected and moved across all of the
plant. This equipment is thought to be invaluable in the area of improvements and it would be the recommendation of this study that any manufacturing plant should have at least one piece of this type of equipment.

### 7.6.1.10 Data from Aluminium Supplier

As the aluminium is the largest cost of any material used in the manufacture of the casting, the secondary aluminium supplier was considered for inclusion in the system boundary. This resulted in some data being collected for energy and waste products but the accuracy is not good because yearly data was collected and averaged across the plant. Although this is not an ideal situation, it still gave a reasonably accurate picture of the plant and is considerably better than the very low grade aggregated data available from other databases which has been sourced from other countries. The aluminium material has thus been omitted from the system boundary but it is worth noting the general results gathered.

The secondary aluminium supplier gathers scrap aluminium in almost any form and supplies the die casting plant with alloyed aluminium to specification. Aluminium dross and oily scrap which cannot be efficiently reprocessed at the die casting plant are sent back to the supplier for reprocessing.

The energy usage at the plant is predictably high with natural gas being used in the smelting process. 10.5 megajoules of natural gas is used per kilogram of aluminium produced in the plant. Added to this is 0.4 megajoules of electricity per kilogram of aluminium. The plant uses sodium chloride and potassium hydroxide to clean and process the aluminium and the majority of this is recycled. Also produced by the plant is 0.4 kilograms of prescribed waste per kilogram of aluminium which is treated off site and disposed of. This information is a generalisation of the process and cannot be considered of high enough quality to be included in the study but is useful to note.

### 7.7 Outputs of the Study

#### 7.7.1 Process Notes

The die casting process generates a large amount of waste with everything except the metal component and the metal scraps (which are recycled) going to waste. The opportunity exists to reuse and recycle many materials used in the process but current technologies are uneconomical and as such are not considered for implementation.

The aluminium which goes to waste has a carbon load of approximately 22 kg CO\textsubscript{2} per kg. Further work in this area could extend the system boundary so as to account for this in the losses. With 5 percent of aluminium going back to the metal supplier as waste (dross, oily scrap, et cetera), not all of this aluminium is recovered so therefore this carbon load is effectively lost with the aluminium.
The die casting process is energy intensive as a process but pales in comparison to the energy required to make the raw material. The energy which is used in the plant is not used efficiently and many opportunities for improvement exist here.

The die casting process is water intensive with approximately 59 million litres of water being used in the plant for the calendar year under study. All of this water is disposed of through the waste water processing equipment at the plant or is lost to evaporation in the process and the cooling towers. Recycling of this water has been considered but once again is uneconomical. Further work is being conducted in this area.

### 7.7.2 Suggested Improvements

In general the suggested improvements target energy usage, water usage and waste minimisation. The improvements are related to advancing the environmental performance of the plant. Since this is directly related to cost, any improvements as suggested here would also become improvements on a cost basis also. What is not suggested here are improvements at any price, since capital constraints are a part of any business although full cost-benefit analysis has not been conducted for these suggestions. The suggestions are itemised by equipment and process. The benefit of this study is not to give a hard number at the end because this number means very little in isolation. It is to give an indication where the major costs and environmental loads are and then be able to target these areas for improvement.

The organisation worked with has a deep culture of continuous improvement and this study has enhanced this. The suggestions developed are not the exclusive thinking of the author but in many cases have come from discussions with plant personnel and management. By working actively in the plant whilst doing this study, all knowledge has been passed where possible, so as improvements can be made immediately. Note is made where suggestions have been, or currently are being, implemented.

#### 7.7.2.1 Cooling Water System

The cooling water system uses two 90 kW pumps to move the cooling water around the plant. These pumps run 24 hours per day, 7 days per week whether production is running or not. This is because the water cannot be left stagnant in the cooling channels of the die because of corrosion. A small amount of water also passes through the furnace door water jacket to cool the furnace doorjams. If this water does not circulate the water will boil causing a rupture and potential explosion. Feasibility studies are being carried out to determine if the pumps can be run with invertors that can reduce the flow when the plant is not in production and possibly turn off one pump. This would save a very large amount of electricity and subsequently reduce emissions associated with this. A side effect would also be a smaller amount of water lost through the cooling water system when the plant is not in use.
7.7.2.2 Compressed Air System

At the beginning of this study when data was being collected it was noted that the usage of energy from the compressors was very high. This was because the compressor management system failed to work most of the time and the compressors would run at a higher pressure continuously, even when not required during non-production periods. The suggestion was made to the plant management to replace the existing system with a Programmable Logic Control (PLC) based system. The plant already had an existing Energy Management System and it was suggested that the compressors could be controlled from this same system.

This suggestion has been implemented and although the exact financial benefits were not available at this time, the management of the compressors is thought to save thousands of dollars of electricity each year which in turn also reduces the environmental load from this activity. The plant management is also able to easily test for and detect leaks in the compressed air system which can potentially waste up to 30 percent of the compressed air used in a plant.

7.7.2.3 Heat Treatment Area

Also during the data collection phase of this project, abnormally high amounts of electricity were being used to heat the quench tanks in the heat treatment area. This was determined to be due to a process fault that had potentially existed for over seven years. The fault has since been rectified saving half of the energy that had previously been used.

To further reduce the energy used to heat this water it is suggested that the heated water is not sprayed into the open air to enter the tank. This reduces the temperature of the water requiring more energy to reheat it. The quench tanks should require very little heating and with proper management could almost be self-sustaining during normal production periods.

Further improvement in the heat treatment area could be realised by batching the loads through different ovens. Currently a heat treatment load is placed into an oven which is electrically heated to solution temperature (>500°C) and held for a number of hours depending on the casting being treated. Most of the energy required for the load is used in the phase of heating the oven and castings to temperature. The castings are then removed from the oven and quenched in water before being placed in the same oven at an aging temperature which is always much lower (<300°C). The waste of the process is allowing all of the heat to escape from the oven being used. Most of the time a number of loads are being treated at the same time. If different ovens were used for solution and aging this energy would not be lost. Other factors such as traceability of load temperature profiles could become difficult but if the monetary saving were high enough this would be worked through in due course. Unfortunately these changes would have a higher environmental benefit than financial but with current electricity prices rising this type of saving could be considered.
7.7.2.4 Melting Furnaces

The melting furnaces used in the plant are over 20 years old and are very inefficient when compared to newer technologies. The efficiency of natural gas use in this area could be doubled with the purchase of new equipment. The cost of this new equipment is not supported by the savings in energy alone and thus labour savings also need to be found in the entire scrap return system. This is possible with automatic loading of scrap into the furnace. Newer furnaces also tend to produce less dross and are inherently safer. This report strongly recommends that new equipment in this area is considered on the grounds of energy savings, labours savings, metal cleanliness, dross reductions and most importantly, safety. Best practice in this area suggests that tower or bridge melting furnaces are a viable option for a plant of this size. Failing this the existing furnaces could be fitted with regenerative burners which would save approximately half of the energy but are quite expensive and do not present the benefits of entirely new equipment.

7.7.2.5 Machine Holding Furnaces

The holding furnaces at the casting machines are a very inefficient design. The cost of replacing these furnaces cannot be justified easily but it is recommended that lids be provided for the furnaces to retain heat during periods of non-production such as die changes and other maintenance, when access to the metal bath of the furnace is not required. New burners with new control systems could also be considered to better maintain furnace temperatures.

7.7.2.6 Metal fluxing

The reverb furnace which melts the scrap is cleaned once daily using flux and nitrogen with a subsequent raking that removes the dross from the top of the metal. This ensures that the furnace refractories are kept clean and the metal is also clean. The furnace is charged and emptied approximately 4 – 5 times daily which means that at best only 25% of the metal coming from the furnace is cleaned. The fluxing releases fluorides into the atmosphere and is also time consuming and dangerous (as it is done small explosions can occur in the furnace). The metal is subsequently cleaned and degassed after leaving the furnace so it would seem the main reason for this action is to clean the furnace. There should be further investigation into changing the flux type (which has happened based on other considerations) and the regularity of the fluxing.

7.7.2.7 Yield Improvements

This study has shown that the single most important variable which can be modified in the casting process to improve environmental performance (and hence cost) is yield. Improvements to the yield have an effect at almost every phase of the HPDC process and the effects would become even more pronounced if the system boundary was extended to include the aluminium material itself. Thus it becomes obvious that the yield of all castings in the plant should be increased if possible.
The best way to ensure the best yield is in die and runner / gating design. Where possible the engineers in the plant do work in this area and computer modelling has been used to improve quality and also reduce the amount of scrap thus increasing the yield. Further work on old dies could be pursued in this area but it is time and resource consuming and is not high on the priority list of the thinly stretched resource of die casting engineers. Original die design with computer modelling can also help to optimise the yield prior to the die being manufactured and this is employed where possible but is not considered accurate enough to be relied on completely.

The only real suggestion is for the die casting engineers and the plant management to recognise how important yield is in both the environmental sense and also the economic sense and for the culture of the plant to be to maximise the yield of all castings from design and through the existing culture of continuous improvement.

7.7.2.8 Die Lubricant

With only approximately 30 percent of the die lubricant used in the plant actually making on to the die surface, the rest goes to waste through the waste treatment plant. This causes two major problems. Firstly it makes the water in the waste treatment plant difficult to recycle and secondly, it wastes a lot of money, making die lubricant one of the highest costs in the plant. If the die lubricant were able to be recycled it would reduce or eliminate these issues.

Work has been looked at in the plant previously in this area but was stopped when a number of problems arose. The recommendation is to revisit this research with the view being to find a way of separating the die lubricant from its contaminants and reusing it. This work has been turned into a formal proof of concept project by the CAST CRC and is continuing.

7.7.2.9 Water

If the die lubricants and other contaminants could be removed economically from the waste water then is could be reused in the plant cooling water system. This could potentially save up to 40 million litres of water per year. Even if this were only 50 percent successful it still represents a large saving in a resource which is becoming more precious all of the time. The current standing is that the chemicals required to treat the water are more expensive than buying fresh water and disposing of waste water. As with the die lubricant recycling recommendation, work is being conducted leading from this study into resolving this problem with the outlook being to reducing waste water from the plant and reusing it in the plant cooling water system.

7.7.2.10 Metal Losses

Metal losses cost the plant large amounts of money each year. Most plants factor in a 3 – 5 percent loss for all metal used in a casting. This is lost as dross from the furnace operations and also from oily scrap from the casting machines. A lot of this waste is unnecessary and can be avoided. Oily scrap results mainly from die surfaces flashing.
This can happen for a number of reasons but most can be avoided or fixed once occurring. The problem becomes critical when it is allowed to continue long periods of time. The metal supplier can reclaim oily scrap outside of the plant but it would make good economic sense to prevent it in the first place. Flashing dies also created maintenance and safety problems which compound the issue and reinforce the recommendation to fix the problem when it first occurs.

Reducing dross is not a simple problem to solve but since most of the dross in the plant comes from the remelt of scrap it would make sense to reduce the amount of scrap remelted. This can be achieved by increasing the yield of the casting as mentioned earlier. New equipment can also help the problem but this does require substantial capital investment and is considered earlier in the discussion.

7.7.2.11 Environmental Management System

The flow chart which has been developed for this study has a number of benefits not only to the study but also to the plant in which the study was conducted. As a visual aid for the process, the flow chart is the first point in identifying all of the process inputs and outputs. For this reason it is useful when a plant is developing an Environmental Management System (EMS) which could be certified to ISO 14001. As part of this EMS a flow chart similar to the one developed for this study is required as the first step in the development of an EMS for the plant.

The following step is the development of an aspect register. An aspect register is a list of the outputs from the manufacturing process and as such this work is generally complete for the plant if it wishes to develop an ISO 14001 EMS. This study was not conducted with the intention of providing a basis for the formulation of an EMS but with the work already completed, a good start could be made by the plant towards this goal.

7.8 Further Work

This project has answered some questions but has raised many more and some of these questions need to be answered. This should happen for the good of the die casting industry from the viewpoint that processes that are not environmentally aware will find survival more difficult in the future. Industry in the future will have to pay a higher cost for damage to the environment. Whether this is from a ‘carbon tax’ or simply by increasing the cost of energy, water and other materials used by the process is uncertain at this time. Other questions need to be answered so as LCA can grow as a process and become part of every design for new products, plants and equipment. If industry works together with the LCA process, both of these can survive and grow.

The main piece of further work that is recommended is the development of the relationship between a casting (generally casting shipped or sold weight) and the emissions from the manufacturing process. This study has shown that this cannot be generalised by studying one casting and using those results to cover every casting made by the same process. This study has also shown that there are relationships
between various process variables (yield) and the emissions from the process (CO$_2$ eq) but at this time those relationships remain unknown. A relationship exists where variables such as the yield and the weight of the casting can be used with a scaling factor to estimate the emissions from the process. This work would require further investigation into the materials involved in the process (improved databases) and allowances for many of the other major process variables mentioned earlier in this chapter.

Further work in the LCA area of the study would include (many of these are interconnected):

1. To complete the LCA – impact assessment would require more data to be collected specifically for the materials involved in the process (localised, time dependant and accurate).

2. Extend the system boundary to include the manufacture of the raw materials involved in the study and also the transport of these materials to the plant.

3. Development of a database for the materials used in die casting (die lubricant, hydraulic oil, et cetera). Data in these materials is so lacking that an entire study could focus on this area.

4. Development of the GaBi3v2 die casting model as presented in this study to incorporate more of the finishing processes and make the whole model work more coherently. This would require considerable further training in the use of the software.

Further work for the Cost-Usage Model:

1. Further development of the CU model to adapt it for other alloys (magnesium, zinc and brass) and other casting processes (gravity, low pressure and sand casting).

2. Discover the best method of manufacture where different paths exist (HPDC Vs LPDC Vs GDC) using the CU model.

3. Discover the best material for manufacture where different options can be considered. This work could use both models and also considering the total life cycle. There are design aspects to this type of work where casting designs are optimised to take advantage of differing casting material’s properties.

4. Further development of the CU model to make it more user friendly. This could enable industry to use the CU model to make improvements to the process and products or as a quotation tool.

5. The CU model could be used to benchmark a plant and compare products and processes within the plant.
Further work in currently being continued by the CAST CRC in the area of waste minimisation to continue on the suggestion of recycling die lubricant and thus enable the possible recycling of plant water into the cooling water system. This has the potential to save many thousands of dollars and many millions of litres of water.

The final area of further work requires industry development of the improvement methodology. This type of research is best if implemented by industry and for this to happen effectively, industry needs to get involved in the development. This ensures the goals of the project are set up to align with the goals of industry. In this approach, research becomes more effective and has a better chance of implementation.

7.9 Conclusion

LCA on a the aluminium HPDC process will give general answers which should not be applied to individual products manufactured by that process unless careful consideration is given. From the results it can be seen that for different cast components manufactured in the same plant, very different results were found.

The process variations that will affect the outcome of the study are the yield of the casting, the size of the HPDC machine, the aluminium type of supply (molten of ingot), the type of furnaces used in the plant and their efficiency, the die lubricant spray time and effectiveness, the water spray of the die surface, the finishing processes used on the die cast component, the labour used in the making of the component and the source of the energy supply to the plant.

Life Cycle Assessment is an acceptable tool for the analysing of the Aluminium High Pressure Die Casting process. By studying the process in the planning phase would give the biggest benefit of LCA.

The data for a LCA study is very important and can also have variation that can affect the outcome of the study. Variation in the data will include, the completeness of the database used, whether the data supplied is aggregated or disaggregated, the country where the data is supplied from, the process from which the data is supplied, the age of the data, the uniformity of the data formatting and the reliability and accuracy of the data.

For the above reasons, the LCA part of this study is considered to have a high degree of inaccuracy. The LCA study can be manipulated to change the results of the study. Moving the system boundary and manipulation of data can alter the results.

A methodology for improvement to the die casting process has been developed, based on the premise that an improvement will either save money, environmental impact or both:

1. Make a flow chart of the process including all parts of the plant directly and indirectly involved in the manufacture of the component under study;
2. Use activity based costing and usage to generate data in the plant. Avoid generalising where possible;

3. Create models of high cost or usage processes within the plant, for example, air compressors and furnaces;

4. Use a life cycle inventory methodology to assess the raw data. Life cycle assessment can be attempted if adequate databases are available;

5. Analyse the results to discover the parts of the process responsible for the highest costs and emissions. The sensitivity of these variables should be checked;

6. Suggest improvements based on the analysis.

The development of the relationship between a die casting and the resulting cost and emissions from its manufacture, in terms of the major variables involved (yield and casting weight) is the most important piece of work suggested to further this study. This knowledge does not currently exist.
References


Pré Consultants B.V. (2001). SimaPro 5.0. Amersfoort, the Netherlands, Pré Consultants B.V.


<table>
<thead>
<tr>
<th>Glossary</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core:</td>
<td>One of the die inserts used to form a hollow section or hole on the casting. Will usually move in and out for casting ejection. A casting may be made from many cores.</td>
</tr>
<tr>
<td>Core Pin:</td>
<td>Similar to a core but is usually smaller and designed to be easily replaced before other parts of the die. May be regularly replaced at services.</td>
</tr>
<tr>
<td>Data - Aggregated:</td>
<td>LCA data that is condensed and not broken up into parts of the process or product. Cannot generally be changed.</td>
</tr>
<tr>
<td>Data - Disaggregated:</td>
<td>LCA data that is broken up into the different parts of a product or process.</td>
</tr>
<tr>
<td>Die Bolster:</td>
<td>Part of the die which holds the inserts in place and connects to the die casting machine platen.</td>
</tr>
<tr>
<td>Die Inserts:</td>
<td>Part of the die that contains the die cavity. The inserts are replaceable and are the only parts of the die to come in regular contact with the metal. These are usually made from tool steels such as H13.</td>
</tr>
<tr>
<td>Die Lubricant:</td>
<td>Sprayed on to the die surface prior to the shot as a barrier to prevent soldering. Usually diluted with water.</td>
</tr>
<tr>
<td>Dross:</td>
<td>Oxides of aluminium and other metal impurities that must be removed from the metal either in the furnace or prior to casting. May form hard spots in the casting or other potential reject problems.</td>
</tr>
<tr>
<td>Flash:</td>
<td>Thin sheets of aluminium formed when small gaps between the fixed and moving halves of the die or between cores allow the molten aluminium out.</td>
</tr>
<tr>
<td>Functional Unit:</td>
<td>The quantity of product that is used to base calculations of material and energy flows across a system.</td>
</tr>
<tr>
<td>Gate:</td>
<td>Entry point of the molten metal into the casting cavity. Connects the casting to the runner and will be one of the narrowest sections which will solidify first.</td>
</tr>
<tr>
<td>Input:</td>
<td>A material that becomes part of the process or product.</td>
</tr>
</tbody>
</table>
**Life Cycle Assessment (LCA):** Compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product or process system throughout its life cycle. (Todd and Curran 1999)

**Life Cycle Impact Assessment (LCIA):** A phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of the product or process system. (Todd and Curran 1999)

**Life Cycle Inventory (LCI):** A phase of LCA involving the accounting of inputs and outputs across a given product or process life cycle.

**Oily Scrap:** Flash and other small pieces of aluminium that get covered in oil when they become detached from the die and fall on to the machine floor. Cannot be remelted in house without prior cleaning. Are usually sold off to metal recyclers.

**Overflows:** Are used vent air from the casting as it fills with molten metal and contain dirty metal and porosity.

**Output:** A material, waste or emission from the process or product.

**Personal Protective Equipment (PPE):** The protective safety equipment used to protect the body / person of operators such as gloves, ear plugs, overalls, glasses, etc..

**Plunger:** Moves the metal from the shot sleeve through the runner and into the die cavity. Transfers the hydraulic pressure to the casting when the biscuit forms at the end of the stroke.

**Porosity:** Small holes in the castings formed when air is trapped inside the molten metal or when large sections solidify.

**Runner:** Directs the flow of the metal from the biscuit to the gate and into the casting.

**Shipped Weight:** Weight of the casting only in final form ready to be shipped.

**Shot:** Each time the metal is poured into the shot sleeve.

**Shot Sleeve:** Where the metal is poured from the furnace into the die casting machine and forms the sleeve for the plunger to move through.

**Shot Weight:** Weight of all of the aluminium poured into the shot sleeve to make the casting including the casting, biscuit, runners, vents and overflows.
**Shrinkage:** The difference between the size of the casting when molten to solid, can also cause shrinkage porosity if the difference is internal on the casting.

**Soldering:** The reaction between the molten aluminium and the iron in the die steel. Will cause the casting to stick to die surface and in severe cases may be the cause of defects resulting in a reject casting.

**Sprue Bush:** Located at the end of the shot sleeve in the fixed half of the die. Forms around the sprue post and is designed to remove heat from the biscuit as the biscuit will be the last part of the shot to solidify.

**Sprue Post:** Located at the end of the shot sleeve in the moving half of the die and forms the first part of the runner. Not used on all dies.

**Venting:** Method of getting rid of air from the casting cavity as it fills with molten metal.

**Warm up:** A casting made to warm up the die by using the heat from the aluminium to get heat into the die. Warm up casting are rejects and cannot be sold.

**Yield:** Shipped weight of the casting divided by the shot weight expressed as a percentage. 100 percent would be a theoretically perfect yield.
Appendix A

Cost-Usage Model Sample Calculations
Appendix A  
Cost Usage Model Sample Calculations

Casting AAs produced 2001 = 323000  
Casting AA rejects produced 2001 = 12228  
Total Casting AAs Produced 2001 = 335228

Reject Rate = 335228 / 12228 = 3.65%

335228 x 1.9915 kg = 667607 kg of Aluminium Melted (dross loss should be added to this.  
(12228 x 1.9915 kg) + (323000 x (0.294 kg + 0.8835 kg)) = 404685 kg Aluminium Scrap to be  
remelted
323000 x 0.814 kg = 262922 kg Aluminium Sold

Aluminium for Plant:  
6627.58 tonnes of aluminium (gross) – dross – oily scrap – turnings  
6627.58 – 200.46 – 64.517 – 35.526 = 6327.077 tonnes net aluminium

Casting AA:  
Shipped weight: 0.814 kg (1.628 kg twin cavity) = 0.814 kg x $2.729 = $2.221 per casting  
Runner: 0.8835 kg (1.767 kg twin cavity)  
Overflows: 0.294 kg (0.588 kg twin cavity)  
Shot Weight: 1.9915 kg (3.983 kg twin cavity)  
Yield: 40.87%

At 80%, on a 23 hour day, 151 days of production would have been required to make the  
335228 AA Castings.

Dross Loss Calculation  
200.46 tonnes of dross produced for 2001  
80% of this dross comes from the remelt of scrap (conservative estimate based on experience).  
200.46 x 0.8 = 160.368 tonnes of dross from scrap  
40.092 tonnes of dross from hot metal delivery and melting of ingots.  
4143.5 tonnes of scrap melted for 2001  
160.368 / 4143.5 = 3.87 %  
6627.58 t of hot metal and ingots through the furnaces  
4953.88 t of hot metal delivered  
40.092 x 25% = 10.024 tonne of dross produced by Reverb 6 (hot metal only)  
10.023 / 4953.88 = 0.2 % dross loss from hot metal  
1673.7 tonnes of ingot and low pressure metal.  
30.069 / 1673.7 = 1.8 % dross loss for other metal, holding furnace skimmings, etc..

Dross Loss:  
Shot weight of hot metal (taken as delivered hot metal) @ 0.2% = 1.9915 x 0.002 = 0.003983kg  
Scrap weight (runner, biscuit and overflows to be remelt in plant) @ 3.87% = (0.8835 + 0.294) x  
0.0387 = 0.045569 kg  
Scrapped castings = (Reject Rate x shot weight) @ 3.87% = (3.65% x 1.9915kg) x 3.87% =  
0.002813 kg  
Total Dross loss for each casting = 0.003983 + 0.045569 + 0.002813 = 0.052365 kg.  
Financial loss = price paid for aluminium – price received for dross = $2729.56 – (20% x  
2729.56) = $2183.648 per tonne = $2.1836 per kg of dross produced.  
0.052365 kg x $2.1836 = $0.1143 per casting

Oily Scrap Calculation:  
95% of Oily Scrap produced by the High Pressure Process. (Estimate based on experience)  
64.517 tonnes of Oily scrap produced by plant for 2001  
0.95 x 64.517 = 61.291 tonnes of oily scrap produced by HPDC  
61.291 / (4953.88 + 735.4) (Molten + Ingot) = 1.077%  
1.077% x casting weight = 1.077% x 0.814kg = 0.00877 kg  
Financial loss = price paid for aluminium – price received for oily scrap = $2729.56 – (18% x  
2729.56) = $2238.24 per tonne = $2.2382 per kg of oily scrap produced.  
0.00877 kg x $2.2382 = $0.0196 per casting

105
5% of Oily Scrap produced by LPDC.

\[
(5\% \times 64.517) \div 938.309 = 0.344\%
\]

Total Metal used per shot = shot weight + dross loss + oily scrap loss + (reject rate x shot wt)

\[
1.9915 + 0.049552 + 0.00877 + (3.65\% \times 1.9915) = 2.12251175 \text{ kg (2.049822 kg)}
\]

The reject rate is included here because I could not think of anywhere else to put it yet.

Nett Metal Used in HPDC = Hot Metal + Ingots – 95% of Oily Scrap – 85% of Dross

\[
4953.88 + 735.4 - 61.291 - 170.391 = 5457.60 \text{ tonnes}
\]

Labour Costs:

Included in the labour cost are all of the personal protective equipment plus all associated costs including Workcover, superannuation etc. as can be seen from the model.

It is important to note that in the overtime calculations a lot of these costs are not included as they are not paid during any extra overtime worked, i.e., annual leave, long service, public holidays, etc..

All labour costs developed per minute, all of these minutes can be converted to dollar amounts, exact labour cost are unclear but are stated in the model for comparative purposes.

Supervision of Casting Labour:

Supervision loading = 10%

\[
\frac{1}{5} \div 2 \times 10\% = 0.110 \text{ minutes per casting}
\]

Casting operator – assumes no operator when there is no production or breakdown:

\[
\frac{60}{60} \div 2 \times (1 + 3.65\%) = 0.51825 \text{ min per casting}
\]

Heat Treat Labour:

This is the labour required to get the casting from the casting machine and conduct the stress relieving process, then return the castings to the packing area.

\[
\frac{100}{1000} = 0.100 \text{ min per casting}
\]

Packing Labour:

\[
\frac{100}{1000} = 0.100 \text{ min per casting}
\]

Furnace Labour:

Minutes to transfer one ladle from furnace to casting machine including pouring, degassing and transfer. Assumes that one ladle goes to one machine only (which is not the case but this would average out evenly so has been assumed).

\[
\frac{2.049822 \times 0.03}{500} = 0.061 \text{ min per casting}
\]

Minutes to transfer one scrap bin to furnace and load into furnace:

\[
\frac{1.1775 \times 0.03}{500} = 0.035 \text{ min per casting}
\]
Fluxing and Raking of Furnaces:
HPDC Tonnage processed each day = 44694 kg
Time required to flux and rake one furnace = 60 min
Number of furnaces operating in HPDC = 2
Amount of metal used per machine per day = no. of castings produced x metal use per casting
= 2304 x 2.049822 = 4722
Labour required for fluxing allocated to the machine = 44694 / 4722 = 10.57%
10.57% x 60 min x 2 furnaces = 12.68 min per machine / 2304 castings = 0.006 min per casting.

Capital Cost:
Bolster:
Cost = $60000
Parts made per bolster set = 4 sets of inserts = 1600000
$60000 / 1600000 = $0.038 per casting

Die Inserts:
Cost of inserts = $70000
Parts per set = 200000 shots = 400000 castings
$70000 / 400000 = $0.175 per casting

Machine Capital cost: (NPV calculation??)
800t Machine = $1500000
Assume Straight Line depreciation over 10 years = $150000 per year
Minutes available to the machine at 220 production days per year =
= 220 days x 24 hours x 60 minutes = 316800 minutes
$150000 / 316800 = $0.4735 per minute

Water Use:
12 nozzels with flow rate of 2-3 litres per second, spraying for 3 seconds of water.
12 x (2.5 x 3 / 60) = 1.5 litres of water per shot
0.75 litres of water per casting

Die Lube Use:
Die lube ratio 70:1
12 nozzels with flow rate of 2-3 litres per second spraying for 3 seconds of die lube
12 x (2.5 x 3 / 60) x 1/71 = 0.02113 litres of die lube per shot
0.010565 litres of die lube per casting = 0.010565 L x $6.147 = $0.065 per casting
12 x (2.5 x 3 / 60) x 70/71 = 1.47887 litres of water
0.739435 litres of water per casting

Tip lube Use:
2cc = 0.002 litres per shot 800T machine
0.001 litres per casting = 0.001 L x $3.005 = $0.003 per casting

Shot Sleeve Life (expected):
40000 shots = 80000 castings – hone (if longer may require grinding or may not be able to be repaired)
Total life = 240000 castings
Initial cost plus reconditioning = $4160 + (2 x $1244) = $6648
$6648 / 240000 = $0.028 per casting

Tip Life (expected):
10000 shots = 20000 castings - resize (4 off resizing)
100000 castings per tip plus labour to resize of 0.25 hours per resizing = 1 hour labour (toolroom)
$485 / 100000 + labour ($50 / 100000) = $0.005 per casting
Casting Labour:
60 second cycle time = 2 castings = 0.5 minutes of labour per casting
Heat treatment requires 100 minutes of labour per load = 1000 casting = 0.1 minutes per casting
Packing requires 100 minutes of labour per 1000 castings = 0.1 minutes per casting
Total labour = 0.7 minutes per casting
If labour = $60 per hour = $1 per minute = $0.70 per casting

Furnace Labour:
2 furnacemen per shift in HPDC = 2 x 7.6 hours x 3 shifts = 45.6 hours = 2376 minutes
if 11 machines running = 2376 / 11 = 248.72 minutes per machine
2208 casting made per day = 248.72 / 2208 = 0.112 minutes per casting

Quality Labour (X-ray and auditor):
2 personnel per shift = 2 x 7.6 hours x 3 shifts = 45.6 hours = 2376 minutes
For all casting machines running = 11 (HPDC) + 7 (LPDC) = 18 machines
2376 / 18 = 132 minutes per machine
132 min / 2208 castings = 0.06 minutes per casting

Validation labour:
30 minutes per validation per casting
30 / 2208 = 0.0136 minutes per casting

Maintenance Labour (Electrician and Fitter) (Breakdowns only)
2 personnel per shift = 2 x 7.6 hours x 3 shifts = 45.6 hours = 2376 minutes
For all casting machines running = 11 (HPDC) + 7 (LPDC) = 18 machines
2376 / 18 = 132 minutes per machine
132 min / 2208 castings = 0.06 minutes per casting

Toolroom Labour (Breakdowns only):
2 personnel per shift = 2 x 7.6 hours x 3 shifts = 45.6 hours = 2376 minutes
For all casting machines running = 11 (HPDC) + 7 (LPDC) = 18 machines
2376 / 18 = 132 minutes per machine
132 min / 2208 castings = 0.06 minutes per casting

Personal Protective Equipment:
Ear Plugs:
approximately 2 pair per person per shift
$0.15 x 2 = $0.30 per person per shift (incidental cost)

Overalls:
2 pair per person per week @ $2.60 per pair
$2.60 x 2 pair / 5 days / 736 castings = $0.001

Cotton gloves:
45858 / 110 personnel using gloves = 400 per person per year
400 / 220 working days = approximately 1.9 pair per shift
1.9 x $0.34 = $0.646 per shift (labour) x 2 men = $1.292
$1.292 / 736 castings = $0.002 per casting

Glass Gripper gloves:
11165 / 110 personnel using gloves = 100 per person per year
100 / 220 working days = approximately 0.45 pair per shift
0.45 x $1.61 = $0.732 per shift (labour) x 2 men = $1.464
$1.464 / 736 castings = $0.002 per casting

Total of PPE = $0.006 per casting
Appendix A
Cost Usage Model Sample Calculations

Forklift Cost:
Lease:
$100000 per year all forks / 6327.077 tonnes net Al = $0.016 per kg
$0.016 x 0.814 kg = $0.013 per casting

LPG:
40,735 litres of LPG at $0.53 per litre
40735 L / 6327077 kg = 0.00644 litres per kg
0.00644 x 0.814 kg = 0.00524 litres per casting
0.00524 x $0.53 = $0.003 per casting

Forklift Total = $0.016 per casting

Other Consumables:
Shot Usage
1010 bags x 25 kg = 25250 kg
6 shotblasters in plant = 4208 kg of shot per shotblaster
70% of PC??? (AA Shotblast 4” Table) used for AA = 2945 kg
2945 / 323000 = 0.00912 kg per casting at $0.91 per kg = $0.008 per casting

Warm Up Release Agent (Silver Grease)
920 litres of Nitrogen at $5.8555 per litre
920 L / 5689.28 tonnes of ADC12 = 0.000162 litres per kg
0.000162 x 0.814 kg = 0.000132 litres per casting
0.000132 x $5.8555 = $0.001 per casting

Melting and Transfer Consumables:
Ross Cone Use:
1 Ross Cone per tap
Tap = 650 kg (average of 2 ladle sizes 500kg and 800kg)
2 kg (Shot weight approx) / 650 kg
0.003 Ross Cones per casting x $0.56 per cone = $0.002 per casting

Flux use (melting)
Allocated on a per kg of ADC12 as furnaces are only fluxed once per day.
10kg Aluxal 100 per day in scrap furnace once per day.
10kg Aluxal 100 in molten delivery furnace once per day.
4953.88 tonnes of molten ADC12 per year + 735.4 tonnes of ingot per year = 5689.28 tonnes per year.
145 drums x 4 bags x 5kg = 2900 kg Aluxal 100 per year.
$12199.40 / 5689.28 tonnes = $2.144 / tonne = $0.002 per kg
$0.002 x 0.814 kg = $0.002 per casting

6627.58 tonnes of Al through the furnaces
$20,496 of Coverall 220 used in plant
$20496 / 6627.58 = $3.093 per tonne = $0.003 per kg
$0.003 x 0.814 kg = $0.003 per casting

Nitrogen (bulk use)
16746 litres of Nitrogen at $0.26 per litre
16746 L / 6327077 kg = 0.00265 litres per kg
0.00265 x 0.814 kg = 0.00215 litres per casting
0.00215 x $0.26 = $0.001 per casting

Thermocouple sheath
107 thermocouple tubes at $67.90
107 / 5689.28 tonnes of ADC12 = 0.00002 sheaths per kg
0.00002 x 0.814kg = 0.00001 sheaths per casting
0.00001 x $67.90 = $0.001 per casting
Appendix A  
Cost Usage Model Sample Calculations

Thermocouple:
162 thermocouples at $25.00
162 / 5689.28 tonnes of ADC12 = 0.00003 thermocouples per kg
0.00003 x 0.814 = 0.00002 thermocouples per casting
0.00002 x $25.00 = 0.001 per casting

Fibreglass Filter Mesh
1 piece 0.5m x 0.5m per shift at $7.84 per m²
0.25 m² / 736 = 0.00034 m² per casting
0.00034 x $7.84 = $0.003 per casting

Melting and Transfer Consumables Total = $0.013 per casting

Fettling:
Hand reamers in pencil grinder = 1 per week
0.2 x $22.80 = $4.56 per day
$4.56 / 2208 castings = $0.002 per casting

Maintenance:
Die and machine maintenance allocated based on machine size on a per tonne of clamping force distribution of an 800T machine is allocated 800/(800x5machines+1250x4machines+2250x2machines). This is a very average way to do it but is a similar way to allocations made by the plant for taxation purposes.
Hydraulic Oil: allocated as to shipped weight which is crap but is the best way I can think of
67000 litres at $2.13619 per litre
6327.077 tonnes net aluminium
67000 / 6327077 = 0.01059 litres per kg
0.01059 x 0.814 kg = 0.0086 litres per casting
0.0086 x $2.13619 = $0.018 per casting

WorkCover:
$443097 / 150 = $2954 per person per year

Energy:
Melting of Scrap:
3.77GJ / tonne of gas
$13.00 per tonne to melt scrap in Reverb 4 or 5 (average taken)
Shot Weight = 1.9915 kg per casting
1.9915 x $0.013 = $0.026 per casting

Holding of Molten:
0.08 GJ per tonne per hour of gas
$0.2713 per tonne per hour in Reverb 6
Assume each kg of metal is held for 6 hours until transfer to casting machine (2 metal deliveries per day)
6 x ($0.2713 / 1000) = $0.0016 per kg
1.9915 kg x $0.0016 = $0.003 per casting

Heat Treatment:
Assume stress relieving cycle performed during day shift.
Oven = 250 kWhr at $0.08666 per kWhr (estimate of usage based on full load profile)
1 kWhr = 3.6MJ
250 kWhr x 3.6 = 900 MJ
900 MJ / 1000 castings = 0.9 MJ per casting
0.9 MJ = 0.25 kWhr = 0.25 x $0.08666 = $0.022 per casting (plus demand charges)
Appendix B

GaBi3v2 Table of Mass Inputs and Outputs
### GaBi3v2 Results Table of Mass Inputs – kg per kg of aluminium die casting

<table>
<thead>
<tr>
<th>Category</th>
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<th>Holding at DC M/C (Crucible/Ladle)</th>
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<th>Brown Coal Power Plant</th>
<th>Natural Gas Transmitted (RMIT)</th>
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<th>Casting and Trim</th>
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<th>Edible portions</th>
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GaBi3v2 Results Table of Mass Outputs – kg per kg of aluminium die casting

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## Appendix B
GaBi3v2 Mass Inputs and Outputs

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<th>Labour</th>
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Appendix C

Compact Disc containing:

1. **Cost Usage Model** – “Cost - Usage Model Generic Casting AA Example.XLS"

This model should be run in Microsoft® Excel 2000. It is a full version of the model with confidential data removed.

Included on this CD is also a Microsoft® Excel 97 viewer which can be installed to view the model. This is only required if the computer being used to view the model **DOES NOT HAVE** Microsoft® Excel 2000 or later installed on it. The following text comes from the Microsoft website:

Microsoft Excel Viewer is a small, freely distributable program that lets users view and print Excel for Windows.

**System Requirements**

- A personal computer with a 486 or higher processor
- Microsoft Windows 95 (or later) operating system or Microsoft Windows NT® Workstation operating system, version 3.51 or later
- 8 MB of memory for Windows 95 and 16 MB of memory for Windows NT Workstation
- 7 MB of hard disk space (9 MB free for installation only)
- VGA or higher-resolution video adapter
- Microsoft Mouse or compatible pointing device
- **Supported Operating Systems**: Windows 2000, Windows 95, Windows 98, Windows NT

**To install this software:**

1. Double-click the **Xlviewer.exe** program file on the CD to start the setup program.
2. Follow the instructions on the screen to complete the installation. **Note** If you already have a full version of Microsoft Excel installed on your computer, **DO NOT** install Microsoft Excel 97 Viewer in the same directory. Doing so will
cause file conflicts. The default folder location in the installer is `c:\Program Files\XLview`.

**Instructions for use:**

To run Microsoft Excel 97 Viewer, do one of the following:

- On the **Start** menu, point to **Programs** and then click **Microsoft Excel 97 Viewer**.
- From the desktop, locate and double-click the `XLview.exe` program file. By default this file is located in the `c:\Program Files\XLview` folder.
- For more information on using Microsoft Excel 97 Viewer, click **Contents** on the **Help** menu in Microsoft Excel 97 Viewer.

**To remove this software:**

1. On the **Start** menu, point to **Settings**, and then click **Control Panel**.
2. Double-click **Add/Remove Programs**.
3. In the **Install/Uninstall** list, select **Microsoft Excel Viewer 97**, and then click **Add/Remove**.
4. Click **Remove All**.
5. Click **Next**.
6. Click **Finish** to complete and exit the installer.

2. **GaBi3v2 Model** – “Michael’ Database

   This has been included for completeness only as there is no viewer available for this software and the view or use the model requires GaBi3v2 Software (or later). This database model is required to be imported into the GaBi3v2® software before being viewed. It contains all of the data as used in the creation of the model of the die casting plant including the transferred data for the energy suppliers and generators.


   It can be viewed in Microsoft® PowerPoint® 2000. Included on this CD is also a Microsoft® PowerPoint 97 viewer which can be installed to view the model. This is only required if the computer being used to view the model **DOES NOT HAVE** Microsoft® PowerPoint 2000 or later installed on it. The following text comes from the Microsoft website:

   Microsoft PowerPoint Viewer is a small, freely distributable program that lets users view and print PowerPoint for Windows.
System Requirements

- A personal computer with a 486 or higher processor
- Microsoft Windows 95 (or later) operating system or Microsoft Windows NT® Workstation operating system, version 3.51 or later
- 8 MB of memory for Windows 95 and 16 MB of memory for Windows NT Workstation
- 7 MB of hard disk space (9 MB free for installation only)
- VGA or higher-resolution video adapter
- Microsoft Mouse or compatible pointing device
- **Supported Operating Systems**: Windows 2000, Windows 95, Windows 98, Windows NT

To install this software:

1. Double-click the Ppview97.exe program file on the CD to start the setup program.
2. Follow the instructions on the screen to complete the installation. **Note** If you already have a full version of Microsoft PowerPoint installed on your computer, DO NOT install Microsoft PowerPoint Viewer in the same directory. Doing so will cause file conflicts. The default folder location in the installer is c:\Program Files\Ppview97.

Instructions for use:

To run Microsoft PowerPoint 97 Viewer, do one of the following:

- On the **Start** menu, point to **Programs** and then click **Microsoft PowerPoint 97 Viewer**.
- From the desktop, locate and double-click the Ppview97.exe program file. By default this file is located in the c:\Program Files\Xppview97 folder.
- For more information on using Microsoft PowerPoint 97 Viewer, click **Contents** on the **Help** menu in Microsoft PowerPoint 97 Viewer.

To remove this software:

1. On the **Start** menu, point to **Settings**, and then click **Control Panel**.
2. Double-click **Add/Remove Programs**.
3. In the **Install/Uninstall** list, select **Microsoft PowerPoint Viewer 97**, and then click **Add/Remove**.
4. Click **Remove All**.
5. Click **Next**.
6. Click **Finish** to complete and exit the installer.

Alternately these posters can be viewed in AutoCAD® LT 97 or later in the files “Process Poster.dwg” and “CAST_Pos.dwg”. This requires the original Software as no viewers are available.
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Appendix D

Paper published in Macro Review 2003

A Life Cycle Inventory of Aluminium Die Casting

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As part of an ongoing project, a life cycle inventory (LCI) of aluminium high pressure die casting (HPDC) has been collected. This has been conducted from the view of an individual product and also the entire process. The objective of the study was to analyse the process and suggest changes to reduce environmental impacts. One modern aluminium high pressure die casting plant located in Victoria, Australia was evaluated and modelled. Site specific data on energy and materials was gathered and the process was modelled using a typical automotive component. The paper also presents our experience and methodology used in this inventory data collection process from the real industry for LCA purposes. The inventory data collected itself reveals that the HPDC process is energy intensive and as such the major emissions were from the use of natural gas fired furnaces and from the brown coal derived electricity. It is also found the large environmental benefits of using secondary aluminium over primary aluminium in the HPDC process. A detailed LCA is being carried out based on the inventory obtained.

1 Introduction

Aluminium die casting is a manufacturing process used to form complex shapes in which molten aluminium is fed into a steel die to solidify. These castings can have a variety of uses from automotive engine blocks to electronic components. Four million tonnes of aluminium is high pressure die cast each year globally with the industry growing worldwide.

Whilst a lot is known and researched about the die casting process itself, very little is known about the environmental consequences of the process. How much aluminium die casting contributes to global warming is a question which is increasingly becoming more important. Life-cycle Assessment (LCA) is a technique that has become common in assessing the environmental impact a product or process. By detailing all of the inputs and outputs to the process or product, a value can be placed on the environmental impact of the process or product. By doing this type of analysis it can also be seen where improvements can be made to lessen the environmental load created by the manufacture of the product.

This paper describes the intermediate phase of an LCA, the Life-cycle Inventory (LCI). This is the collection of all of the data without the full analysis of normalisation and weighting. An LCI allows the amounts of each of the inputs and outputs of a process to be shown in a raw form. This enables only a rough analysis but is useful to show high usage or wastage as is the case with this study.

2 Methods

This study was performed in accordance with the ISO14040 series of standards for LCA [1]. Site specific data was gathered from the site of one aluminium die casting plant. As many inputs as data was available for have been used in this study and all emissions have been included from the site where possible.

2.1 Site - High Pressure Die Casting Plant

The site where all of the data was collected is located in Victoria, Australia. All of the die castings made in the plant are for automotive use. The site has an annual production of 7000 tonnes of aluminium per year and all of the data collected for this study was for the year 2001.

2.2 Process - High Pressure Die Casting

The high pressure die casting (HPDC) process was chosen as it is one of the major casting processes used by the automotive industry to manufacture aluminium components. The HPDC process as used at this site has been broken down into seven major parts as can be seen from Figure 1.

The ‘ingot’ phase consists of aluminium ingots or molten aluminium delivered to the plant and for this study includes the secondary aluminium supplier. The ‘melting’ of the ingots or storage of the molten aluminium in the second phase of the process, was accomplished in natural gas fired reverberation furnaces. It will be raked and cleaned to remove the dirty metal and dross. A fork truck was used to move the metal from the reverberatory furnace to the holding furnace at the machine. The metal was cleaned between these two furnaces using a flux and nitrogen gas and the metal was held at the machine in a natural gas fired crucible furnace. A robotic arm with a ladle attached transfers the metal from the furnace to the shot sleeve of the die casting machine.

During the casting phase a piston moves behind the metal that has been poured into the shot sleeve, forcing the metal into the die at very high pressure. After the metal solidifies the pressure is released and the die opens. The part is ejected and removed from the die and the die faces sprayed with a release agent generally known as die lubricant so as the aluminium will not stick to the die. The number of finishing operations available to a die casting is very extensive but nearly all die castings will be trimmed to remove the biscuit and runners that are then recycled within the plant. From here the casting can go
through common operations such as fettling and shotblasting to remove sharp edges and loose aluminium. All castings are packed in or on something to be shipped to the customer.

For this study an automotive transmission cover manufactured at the site was followed through the high pressure die casting process. The casting selected was cast in a twin cavity die and had a shipped weight less than 1 kg.

![Die casting process](image)

**Figure 1. Die casting process**

2.3 *Functional Unit and System Boundary*

The functional unit for this study was per 1 kilogram of aluminium shipped. This unit broadly describes the process and all data was scaled to fit this unit.

The system boundary for this study was considered to be the plant / site boundary. Transport of all inputs into the process has not been considered and also transport of the finished product to the customer has not been considered. All activities within the site have been considered. Capital equipment has also not been studied. Where data has been available, the system boundary has been extended to cover energy sources and materials such as the secondary aluminium used at the site.

2.4 *Data Collection*

The process was broadly described and then detailed so as not to exclude any items that were used in the plant or in the manufacture of the component under study. The process was broken down into its individual components as described earlier. By analysing each of these units separately, all of the inputs and outputs were captured.

Data capture is the most time consuming part of any life cycle inventory. As the data will vary for different localities, time must be taken to ensure that the data used is relevant. Site specific data was captured by collecting all data from the stores. This ensured that all items used in the plant could be captured. Of the 3000 items listed in the stores only approximately 250 were considered for the study because of other processes used at the site and also items that were of low volumes were also discarded or grouped together. This data was then compared with knowledge from the personnel at site for consistency. Any data that conflicted has been adjusted as per the site’s internal standards.

All electricity, natural gas and water use was collected for the plant. Furnaces were monitored where possible and meters placed on equipment to determine exact energy usage. Where this was not possible estimates have been used based on equipment ratings, motor sizes, burner sizes and old data. Any extra data that is not generally found was also collected. Major repairs to capital equipment was also collected such as furnace refractory replacement.

All of this data was sorted and entered firstly into a spreadsheet and then into GaBi3v23v2 [2] life cycle software. Using this software and its associated database enabled the inputs and outputs from the process to be effectively grouped and overall results gathered.

2.5 *Allocation*

A specific component was followed through the process so as all inputs and outputs could be allocated to the functional unit. An activity based allocation method has been used with actual amounts of all inputs measured. Where possible outputs were also measured but it was more common to calculate these from the inputs. Where measurement was not practical, amounts were allocated by the functional unit in relation to the rest of the plant.

3 *Results*

When recyclable metals are removed, all other outputs from the process go to waste (landfill, air and water emissions, etc.). For each kg of aluminium shipped, 8.6 MJ of natural gas and 5.8 MJ of electricity is consumed in the plant. This is broken down according to Tables 1 & 2.

<table>
<thead>
<tr>
<th>Table 1. Natural Gas Use per Casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2. Electricity Use per Casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
</tr>
</tbody>
</table>
Holding of Molten Metal 1.174
Remelt of Scrap 5.194
Holding at Machine 2.048
Other 0.184
Total 8.600
Casting Machine 1.843
Air Compressors 0.999
Cooling Water 0.646
Heat Treatment 1.548
Other 0.796
Total 5.832

For this study the results were broken up into many categories. The results for the categories of Global Warming Potential Over 100 years (GWP 100) and Human Toxicity Potential (HTP) are presented in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>GWP 100 (CO₂ Equivalent)</th>
<th>HTP (DCB Equivalent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0.8181</td>
<td>0.004541</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1.1451</td>
<td>0.002651</td>
</tr>
<tr>
<td>LPG</td>
<td>0.0191</td>
<td>0.001391</td>
</tr>
<tr>
<td>Aluminium Supply</td>
<td>1.0629</td>
<td>0.003157</td>
</tr>
<tr>
<td>Other</td>
<td>0.0040</td>
<td>0.000155</td>
</tr>
<tr>
<td>Total</td>
<td>3.0492</td>
<td>0.011895</td>
</tr>
</tbody>
</table>

The GWP results are all emissions to air and are all from energy production and use. The large amount of natural gas used is because of a cost advantage over electricity. All electricity used is considered to be from base load power that is generated by brown coal fired power stations in Victoria. The HTP results are a combination of releases of substances such as heavy metals into the air, water and to land. These are also generally released from energy production and use. Other items considered for the study such as Acidification Potential also showed a relationship to energy. The large amount of water used in the process is the only result that was high and not directly related to energy production or use.

4 Discussion

4.1 Methodological Considerations

The LCI methodology requires everything to be allocated by the functional unit. By using the functional unit of per kilogram of aluminium shipped for the study has introduced a large variation that makes the study an inaccurate generalisation for the process.

Using this functional unit does imply correctly that for every kilogram of aluminium shipped there is more than one kilogram of aluminium melted and used. Metal losses such as dross will vary according to how much aluminium is melted and cast. Although these have been allowed for in the study, actual results will vary from cast product to product. The yield of the casting (how much is shipped divided by how much is cast) changes from casting to casting and this has been found to create a large variable in the results.

4.2 Process Variations

The Aluminium HPDC process itself has approximately 200 variables that can be modified and will have an affect on the outcome of the LCI. From the results it was found that the amount of scrap that was remelted from each casting is the variable that had the single biggest affect on any of the categories measured. This can vary by up to 10% for each individual casting produced at the site. A 10mm increase in scrap length will result in a 1% increase in CO₂ emissions. The variation within the process itself, the range of suppliers of materials to the site, all the way to energy used at the site and its variability make it erroneous to take absolute numbers from the results. The numbers will not be repeatable and will vary from casting to casting and site to site.

4.3 Data Accuracy

The most important area of a LCI is the data. Access to ‘real’ data makes this study more accurate than otherwise possible. Actual usage of all major materials, reliable data from energy sources local to the plant and reliable data from the secondary aluminium supplier is the strength of this study. A reliance on LCA data with unknown origins is the weakness of this study and the LCA technique.

Any study is only as good as the data used. For most of the materials entering the site actual data was not available and estimations from available databases have been made. When available, data is in aggregated or disaggregated form. If aggregated the user has no knowledge of the data except for the end result.
result. This data, although not preferred, must sometimes be used and will lead to inaccuracies with any LCI or LCA study. With data being variable in areas such as location, time, method of collection and storage it will continue to be the weakest link in the LCA area of study. Within the Life Cycle Assessment scientific community this is a known challenge and is being confronted by a United Nations initiative.

5 Conclusion
A Life-cycle Inventory is a useful tool to determine the environmental consequences of a product. In the case of this study it has been applied to an individual component with an accurate result. The further Life-cycle Assessment will further reveal the environmental impacts of the inventory. When the results from an LCI or LCA are taken from one product and applied to the process used to manufacture the product the results can be flawed. To generalise the HPDC process by studying one component will lead to incorrect findings.

By analysing the findings for the one component can lead to improvements to the process as used to manufacture this one component. It can be seen from the LCI that wastage is high in the process and this is one area for improvement. Energy usage is also high and the majority if the inventory comes from this area and any improvement will reduce the impact this product has on the environment.

An LCI and LCA when conducted on aluminium high pressure die casting should not be used as an absolute tool but should be used as a comparative tool concentrating on the individual product and not trying to generalise the process by which it is made.

Further work in this study will be the LCA of this component with the addition of cost into the assessment as this is one of the biggest driving factors for improvement for the site where this work was conducted.

6 Acknowledgements
The authors wish to acknowledge the CAST CRC for funding this study and the RMIT Centre for Design for making reliable LCA data available in the public domain.

References