UNIVERSITY OF JOHANNESBURG

Towards green manufacturing: improving environmental sustainability in the Zimbabwean steel industry

by

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Dedication

To my husband, Stephano.

this is our third thesis, together
you are extraordinary, superb, magnificent, staggering, incredible, wonderful, phenomenal, remarkable, spectacular … list is endless

To my mother, Mum, Majede.
you taught me how to read my first English word
you taught me how to count my first number

Abstract

This research focused on identifying ways of contributing towards green manufacturing by improving environmental sustainability in the Zimbabwean steel industry. The research was carried out through literature search, industrial surveys that included interviews of key personnel and the use of a questionnaire, and experiments to verify a hypothesis that was formulated. The industrial survey utilised the Delphi approach in order to explore the strategies, tactics and practices that the companies in the steel industry are currently implementing, and other improvements needed in order to ensure economic, social and environmental sustainability. It also identified current processes and any mitigation methods in place to mitigate emissions of toxic gases and allowed for interviews of key personnel from which a questionnaire was then formulated. The main concern for all the companies represented was that policies need to be investor friendly as that would lead to economic sustainability which in turn would lead to improved social and environmental sustainability. The results of the survey were distributed to all participants for further implementation of possible environmentally friendly practices.

From the survey a hypothesis was formulated that cupola furnace slag may be used as a lubricant in the cutting of steel. Two samples of the cupola furnace slag were collected from two different companies and ground into powders. Experiments were set up using soluble oil as the control experiment and the powders were used as dry lubricants and Vaseline was added to produce a paste. The results showed that cupola furnace slag may be used as a lubricant in the cutting of steel as it outperformed oil-based cutting fluids. It has lubricating properties and is capable of inhibiting heat diffusion.

Another industrial process investigated was calcination for a new start-up company. Calcination is an endothermic reaction that converts limestone into lime. Making the calcination process greener was studied and ways of achieving this were identified as: addition of chimneys to the kilns to increase draught column and allow preheating of limestone, addition of exhaust allowing the flue gases to pass through an amine system as a means to strip the flue gas of CO_2, and use of insulating material such as vermiculite between the inner brick skin and outer brick layer to optimise energy utilisation.

The main contribution to knowledge was that a new solution to the utilisation of cupola furnace slag was established. This will economically assist the companies by cutting out the purchases of soluble oil and commercializing the use of cupola furnace slag in cutting. Reduction of cupola furnace slag in landfills is a great contribution towards sustaining the environment and greener manufacturing. The selection of slag that has a high aluminium and silicon content will help in its use as a solid lubricant in dry drilling. It is also noted that both aluminium and silicon are key constituents of coatings for cutting tools. Promoting dry drilling will also advance sustainability by reducing the use of oil-based cutting fluids thus cutting costs and eliminating the environmental burden of oil usage.

The Industrial Impact was that companies that took part in the study are very happy with the results of the dry drilling. They now have a low-cost consumable for machining for their in-house operations or for commercialisation. Wider sustainability factors for Zimbabwe steel industry were also covered. The study has developed and documented the industry preferred solutions for promoting the revival of the Zimbabwe steel industry. The three main contributions to knowledge made by this research are solutions for the revival of the Zimbabwe steel industry, a new method for deriving value from slag waste and firm proposals for reducing emissions in the calcination plant.

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Chapter 1

INTRODUCTION

1.1 Research Background and Context

Sustainability in industry has in the recent years been considered more seriously in the world. It is considered to be a solution for development and growth in manufacturing (Latif et al., 2017). The importance of utilising energy from renewable sources, correctly managing waste, and increasingly preserving the environment are growing daily. In Africa there is economic development and speedy demographic increases in many countries and this without fail affects the environment. However, a lot of the carbon footprint research has mostly focused on the industrialised nations and not much is known about the causes of energy related CO_2 discharges and their effects on the environment in African nations. Table 1 shows data for some African countries. These are figures of the embodied carbon in production, consumption, trade and the balance of emissions embodied in trade (BEET). This is the net export of embodied emissions as a percentage portion of production-based emissions.

Table 1.1: Embodied carbon in fabrication, exports and imports (He and Wang, 2017).

Country	Production (Mt CO_2)	Consumption (Mt CO_2)	Exports (Mt CO_2)	Imports (Mt CO_2)	BEET (%)
Botswana	4.45	7.38	2.91	5.84	-65.89
Cameroon	5.35	6.16	1.50	2.31	-15.10
Egypt	161.34	142.50	47.27	28.42	11.68
Ghana	9.28	12.76	2.59	6.07	-37.54
Mauritius	3.31	3.35	2.93	2.96	-1.11
Mozambique	2.25	4.36	4.27	6.39	-94.36
Nigeria	53.85	50.61	27.99	24.75	6.01
Senegal	4.99	6.34	1.76	3.10	-29.96
South Africa	342.22	271.21	120.36	49.35	20.75
Tunisia	21.72	21.48	12.50	12.27	1.06
Zambia	1.34	2.56	2.01	3.24	-91.80
Zimbabwe	8.93	7.39	5.24	3.71	17.19
Rest of North Africa	122.94	12.51	28.39	26.97	1.16
Rest of Southern Africa	1.02	1.20	0.74	0.91	-16.73

The balance of emissions embodied in trade outcomes in Table 1.1 indicates that only 6 nations, namely South Africa, Nigeria, Tunisia, Zimbabwe, Egypt and Rest of North Africa are overall exporters of the embodied carbon while the other countries are overall importers of the discharges. The variances in embodied CO_2 discharges across all these countries may then impact differently on the sense of obligation of specific countries to current and future global environmental policies as well as autonomous emission reduction opportunities (Asane-Otoo, 2015). This may well imply that abatement of harmful emissions in Africa still requires serious efforts on individual country basis. Therefore, every effort that leads to reduction of these emissions is necessary. In Zimbabwe the production of steel and its products is the backbone of the country's industry. Achieving environmental sustainability in steel works would go a long way in the country's efforts to reduce greenhouse gas emissions.

1.2 The World Steel Industry vs the Zimbabwean Steel Industry

Raw steel manufactured worldwide was only 28.3 Mt in 1900, it then rose to 100 Mt in 1936, and proceeded to exceed 200 Mt in 1951, and got to 850 Mt in the year 2000. In the 2000's, the world raw steel manufactured soared to 1670 Mt in 2014 (He and Wang, 2017). This increase is as shown in Figure 1.1.

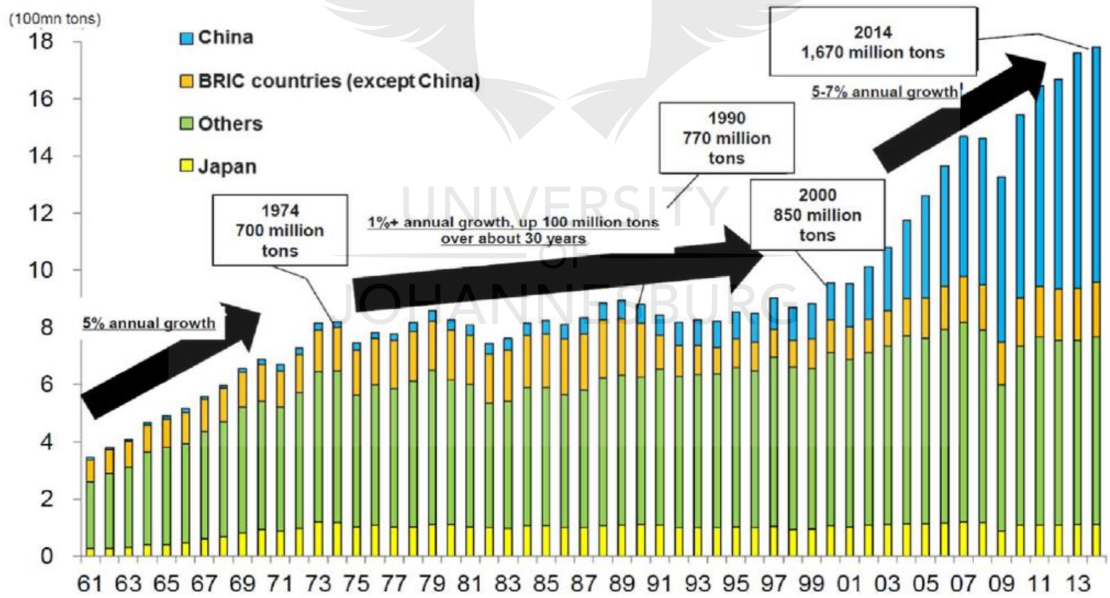


Figure 1.1: World raw steel manufacture quantities increasing over the years (He and Wang, 2017)

Production of steel requires high levels of energy and huge amounts of other resources. In the year 2013, 18% of the world's total energy utilised in industry was used in the iron and steel division. The efficient use of energy in the iron and steel industry affects directly the total energy utilisation. Therefore, the primary concern for iron and steel foundries has to be enhancing the optimum use of energy, particularly when prices of energy are volatile. Currently, the steel industry has the technical know-how of dropping the present overall energy utilisation by about 20% through the use of superlative technology that is available (He and Wang, 2017). It was also reported that 3%–4% of all the harmful gas emissions in the world come from the iron and steel sector in the industry (Chen and Zhang, 2010). Many different approaches are being used to reduce these emissions in the fabrication of steel. These include recycling of granulated blast furnace slag and several ways of capturing CO_2 during the processing of iron and steel.

In Zimbabwe the worst economic crises were experienced during the years 2004 and 2009. The main reason for this collapse was hyperinflation that reached a peak of 2.5 million percent a year in June 2008. This hyperinflation destroyed the economy and the living standards plummeted by 38 percent (Hanke, 2008). In such an economic environment the steel industry was not spared. The reduction in steel production is illustrated in Figure 1.2:

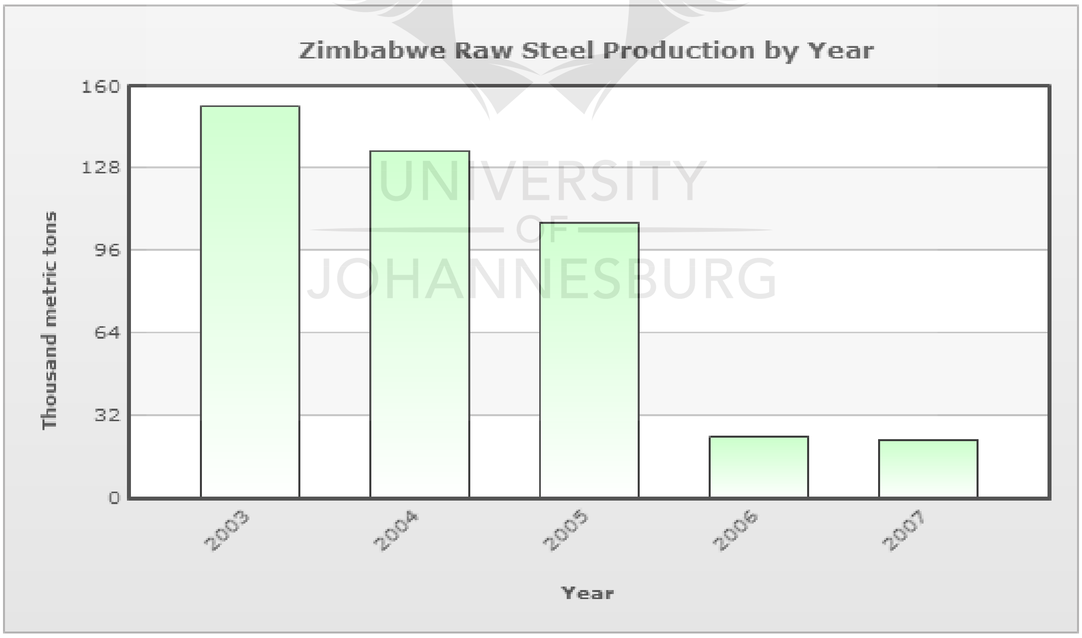


Figure 1.2: Zimbabwe Yearly Raw Steel Production (Index Mundi, 2013)

Nevertheless, in February 2009 a multicurrency system was introduced (Kararach et al., 2010) and (Kramarenko et al., 2010), and the production in the iron and steel industry was estimated to have started growing. With the exception of the biggest supplier of crude steel, a parastatal, that is yet to resume its processing the smaller steel companies boosted production in response to the multi-currency system. The economy then continued to fluctuate over the years and this has affected the steel industry accordingly. Foreign investors have shown positive interest in rehabilitating the parastatal that is potentially the largest supplier of crude steel in the country (Tripathi et al., 2012). This move would instantly resuscitate and regrow the country's steel industry as a whole.

1.3 Problem Statement

As a country's economy fluctuates, sustainability becomes a key issue. The steel industry in Zimbabwe is the backbone of the country's industry, thus sustainability in all its facets in the steel industry can underpin sustainability for the Zimbabwean industry. This means that environmental sustainability in the Zimbabwean steel industry requires immediate attention.

1.4 Research Question

The main question to be answered is: How can sustainability be promoted in the Zimbabwean steel industry?

1.5 Objectives

1.5.1 Aim

The main objective of this research is to identify ways of accomplishing sustainability in the Zimbabwean steel industry in the drive towards greener manufacturing.

1.5.2 Specific Objectives

a) To identify the barriers and potential solutions for economic sustainability of the steel industry in Zimbabwe.
b) To assess the resource usage e.g. energy and water in the steel industry
c) To explore beneficial ways of deriving value from furnace waste.
d) To explore ways of reducing carbon and other greenhouse gas emissions during calcination.

Chapter 2

LITERATURE REVIEW & METHODOLOGY

2.1 Green Manufacturing

As the manufacturing industry and the number of people grow, additional waste is created, extra energy is utilised as more products are required. Green manufacturing approaches product and process design with the environmental concerns being the top priority instead of a trivial limitation. It stresses the validity of environmental factors consistently with all the necessities of product quality and budget (Franchetti et al., 2009).

Six goals that define green manufacturing are:

- Identify and use materials that impact the environment less.
- Do not use hazardous or lethal resources.
- Select greener production procedures.
- Maximize efficiencies of energy and water.
- Design to minimise waste.
- Design to recycle and reuse resources.

The need to be environmentally conscious in manufacturing is becoming more and more crucial because manufacturing processes generally have some effect on the environment. Therefore, all designs must cater for the potential environmental effects at all design levels (Franchetti et al., 2009). One outstanding way of applying this approach methodically is Lean Manufacturing. Generally, Lean Manufacturing requires that products be designed and fabricated with a view towards lessening material utilisation and, if possible, totally removing waste and pollution. This means that the design must factor in how a product will be discarded, at the end of its life, into the fabrication procedure. The process starts from product design right through to fabrication, supplying, and discarding or recycling. Lean Manufacturing is the collection of strategic procedures that highlight removing actions that do not add value i.e. the waste, while distributing good quality products at minimum cost with superior effectiveness (Franchetti et al., 2009). Waste is any action in a procedure that does not add value to the consumer. Lean Manufacturing identifies numerous kinds of waste.

These may be producing more than requirements, imperfections, waiting and more than necessary inventory. In order to become lean and environmentally friendly, manufacturing companies need to redesign, restructure, re-engineer, and retool operations and processes to ensure more environmental and social sustainability. In this setting, implementation of lean manufacturing way of doing things can advance the organization's environmental performance (Sobral et al., 2013).

Lean manufacturing transferred to green manufacturing has yielded good outcomes. Young and McClean, (2009) reported on the change from lean to green approach by manufacturing companies in Australia. The waste taken to junkyards was minimised by up to 80% and this was a brilliant outcome.

Diaz-Elsayed et al., (2013) identified a method of integrating lean and green approaches into a manufacturing scheme from gathering of data to the assessment of a scheme. Additionally, a detailed examination was carried out for a part fabrication in the automotive subdivision, and a custom-made combination of lean and green approaches was implemented. It resulted in a drop of about 10.8% of the fabrication costs of the specific part.

Green Manufacturing can be replaced with Sustainable Manufacturing. Sustainable Manufacturing may be defined in two ways as firstly: the fabrication of products using methods that lessen environment-damaging effects, preserve energy and natural resources, are harmless to workers, neighbourhoods and users and are economically viable. This involves creation of renewable energy, energy efficiency, green construction, and the like. Secondly: sustainable manufacturing involves the fabrication of sustainable products using sustainable processes. This emphasizes the sustainable fabrication of all products considering the life-cycle sustainability matters linked to the products fabricated. Manufacturing is the principal process in a tangible product's supply chain. Designing the manufacturing system and encouraging sustainability in its processes must concentrate on a sustainable manufacturing method, that is, an innovation-based 6R methodology to reduce, reuse and recycle, recover, redesign, and remanufacture the products over numerous life-cycles (Jayal et al., 2010). In this 6R practice:

- ‘reduce’ mostly centres on the initial three phases of the product life-cycle and points to the reduced utilisation of material in pre-fabrication, reduced utilisation of energy and resources in fabrication and the reduction of waste during use
- ‘reuse' points to the reuse of the product or its parts after its initial life-cycle, for following life-cycles to lessen the use of new raw materials
- ‘recycle’ includes changing stuff that would ordinarily be waste into new resources or products
- ‘recover' is the collection of products at the conclusion of the usage phase, stripping them, arranging and cleaning them for use in succeeding life-cycles of the product
- ‘redesign’ of products is making simpler upcoming post-utilisation procedures through the implementation of methods, such as Design for Environment, to make the products more sustainable
- ‘remanufacture’ involves the re-processing of previously used products, refurbishing them to their initial or a near-new state through the reuse of all parts possible without losing their functionality (Jayal et al., 2010)

Greener manufacturing requires immediate implementation on all levels. Worldwide, temperature is rising as a result of harmful emissions, especially carbon dioxide. Huesemann, (2006) noted that the most severe emission situations would end in a global temperature rise of at least 2^{o}C by 2100. The undue earth and atmosphere temperature rise has negative effect on the environment, which in turn affects all the living creatures. There is doubt linked to these prognoses, however risks associated with 2 °C rise and beyond mean that the climate will progressively heat up and likely impacts are visible on sea levels and extinction of some species (James and Washington, 2013).

The move to decrease fossil fuel utilisation and greenhouse gas emissions takes the lead in greener manufacturing. Ma et al., (2012) showed that it is hard to regulate SO_2 emissions to tolerable levels by just improving technology and bringing in industrial structural modifications. But by including removal of sulphur from sintering gas, more SO_2 emissions are abated and the intended value is reached more easily, since sintering is the chief emitter in this industry. So, to manage the total SO_2 discharges of the steel industry it is necessary that two or more actions be used simultaneously.

The world as a whole is analysing and implementing ways of reducing greenhouse gas emissions. This research will focus on analysing means of reducing greenhouse emissions, especially CO_2, during manufacturing of steel as a means to greener manufacturing and the sustenance of the environment.

2.2 Steel

Steelmaking has played a vital role in the growth and expansion of the modern-day technological world. Steel is an iron-carbon alloy. Steels may also contain other elements in varying proportion. For example, other alloying compounds such as chromium, manganese, and silicon are purposefully supplemented to alter the properties of steel. Heat treatment also affects the properties of steel (Green J et al., 2013):

- *Chromium Ferroalloys in Steel-making*

The main use of chromium ferroalloys is in the fabrication of stainless steels. This is because chromium supplies a protecting layer of its oxide when it is more than 11% in the steel.

- *Manganese Ferroalloys in Steel-making*

Manganese reacts with oxygen more easily and faster than iron and therefore deoxidizes steel. For this reason, it is used in many grades of steel. This reaction is even stronger when it is mixed with silicon as silicomanganese alloy.

- *Silicon Ferroalloys in Steel-making*

Silicon is a robust deoxidant. It is used to deoxidize steel and as an alloying agent too. Its strong affinity for oxygen is utilised in the deoxidation process. The process is more effective when silicon is used together with manganese because the two form an intricate silicate (Lee, 2001). The characteristics of steel strongly depend on the amounts of alloying elements added, thus the levels of alloying elements are monitored meticulously during fabrication of steel.

- *Effects of heat treatment on Steel properties*

Isfahany et al., (2011) researched the effect of heat treatment on mechanical properties of AlSi 420 martensitic stainless steel and concluded that optimizing austenitizing and tempering temperature and time during heat treating gave an acceptable blend of mechanical properties to AISi 420 steel. Austenitizing at 1050 °C brought about an impact toughness of 30J, an extreme hardness of 50 RC and strength of 1900 MPa. Srivatsa et all., (2016) also concluded that impact toughness is improved by hot working and heat treating 13% Cr martensitic stainless steel. The impact toughness was doubled when the steel bars were subjected to a single hardening heat treating at 980 °C and oil quenching at 1040 °C and a double hardening heat treating at 1040 °C and oil quenching at 980 °C. This was then followed by a typical two stage tempering at 710 °C and at 680 °C. This shows that heat treating Steel improves its mechanical properties.

Steel is ductile and workable, and has proved to be a versatile material. Therefore, steel is utilised in construction, generation and distribution of power, agriculture, medicine and production of industrial and household machinery.

2.3 The General Manufacturing Process of Steel

For the most part of human history, steel was made only in small measures. In 1858 a major invention came about when a Bessemer converter was invented with an open top, shown in Figure 2.1. The converter was first tilted to a horizontal position and molten iron added in then rotated to the initial vertical position and a blast of hot air blown in continuously through the tuyeres to chemically react with unwanted compounds.

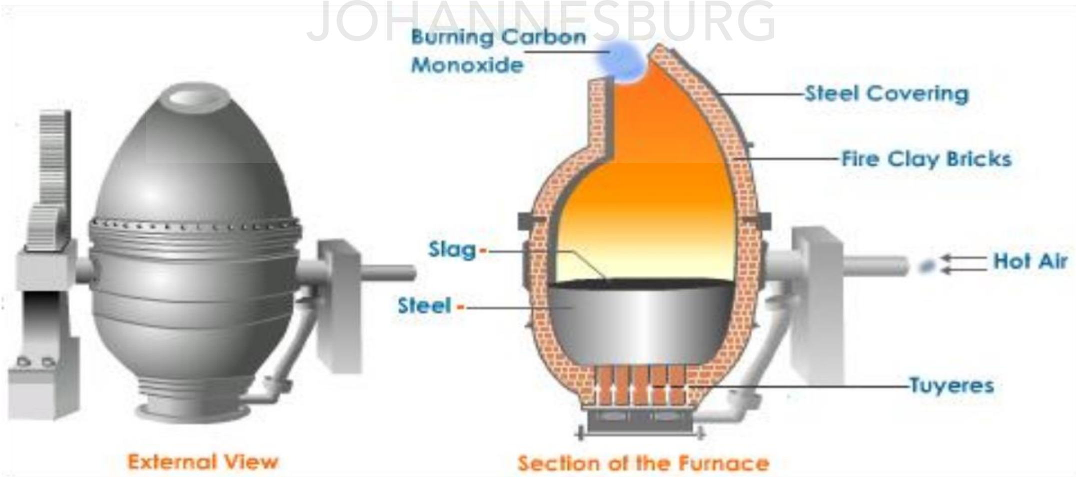


Figure 2.1: Bessemer converter, schematic diagram and components (Bessemer, 1855)

As it travelled up through the converter, the air oxidised the impurities in iron. Silicon and manganese were the first to be oxidised in the first 5 to 10 minutes. Carbon monoxide was released later, and it burned with a blue flame at the entrance/exit of the converter. The blue flame died out when all the carbon was oxidised. The steelmaker knew that when the conversion was complete the flames disappeared. The essential quantity of carbon was then added to transform iron into steel. Waste slag would be easily taken off from the upper part of the molten steel. The oxidation raised the temperature as well and kept it as a liquid (Misa, 1998). The Bessemer method was the low-cost industrial procedure for the high-volume production of steel from molten iron before the open-hearth furnace was invented.

Modern steelmaking processes can be categorised in two ways as:

- the blast furnace way (the primary way) which utilises 70% to 100% of iron ore and the rest being scrap
- the electric arc furnace way (the secondary way) which utilizes 70% to 100% scrap material scrap and cast iron, the rest being made up of ore-based materials.

The main difference between the two modern steelmaking processes is the kind of raw materials used. In the blast furnace the raw materials are mainly iron ore, coal, and recycled steel (in order of the highest quantity). In the electric arc furnace, steel is produced using mostly recycled steel and electricity. The electric arc furnace uses less energy than the blast furnace. Substantial energy can be saved by changing from blast furnace to electric arc furnace fabrication. But such a change may be limited by the convenience of accessing the scrap and the need for better grades of steel. After either of the processes liquid steel is then solidified into continuous casting machines and numerous profiles are formed as it goes through a series of hot and cold procedures. These profiles, treated or not are then sold to producers of innumerable steel products such as construction frames, beams, automobile frames, and farming equipment (He and Wang, 2017).

The different ways of producing steel are shown in Figure 2.2. The primary steel making process is disjointed; in-between it includes that transfer from the blast furnace and discharge, pre-treatment of hot metal to remove sulphur and slag, transfer, weighing and reladling (Remus et al., 2013).

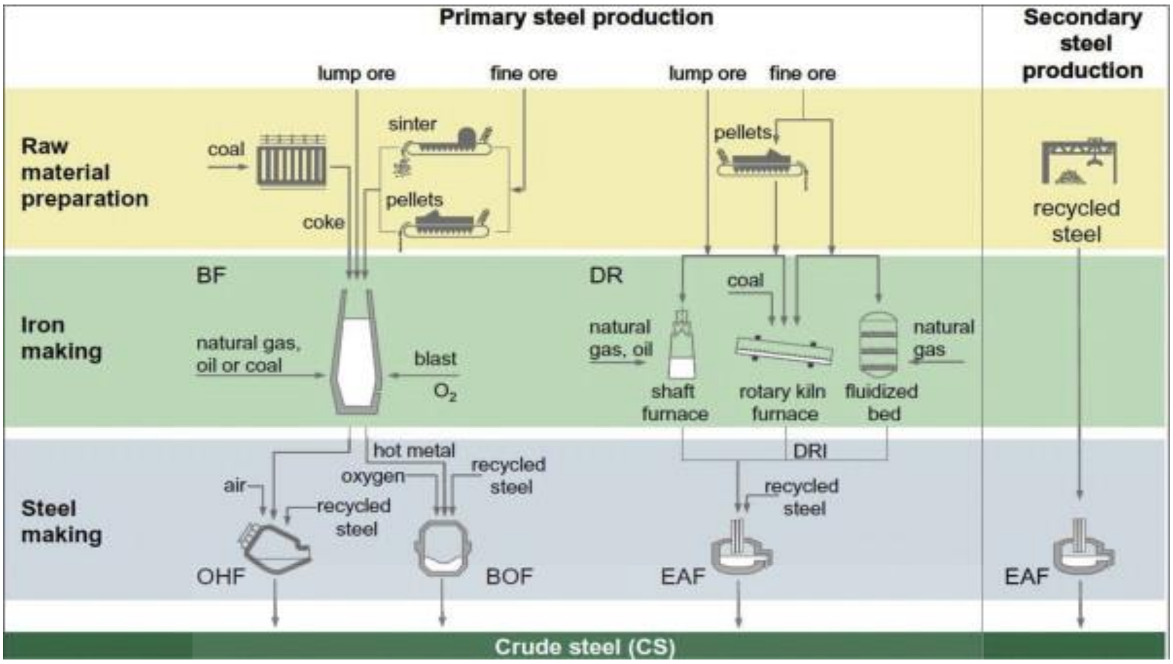


Figure 2.2: Primary and secondary ways of making steel (Oliveira et al., 2015)

In the primary way of making steel iron making is done the blast furnace (BF) way or the direct reduction (DR) way. From the blast furnace crude steel is then produced in the open-hearth furnace (OHF) or the basic oxygen furnace (BOF). In the direct reduction process the direct reduced iron (DRI) is mixed with recycled steel in the electric arc furnace (EAF) and thus producing crude steel (Oliveira et al., 2015). This primary process leads to the production of ingots that will then become raw materials in other processes. The secondary way of making steel produces crude steel from recycled steel in the electric arc furnace. This process generally continues into some other processing of the steel such as casting and/or rolling. Greenhouse gases are produced during the production of molten iron. These include carbon dioxide and carbon monoxide (Remus et al., 2013).

The steel making process continued to become more advanced. From the time oxygen was first used on an industrial scale the mechanisms for blowing oxygen into the bath of open-hearth furnaces and electric arc furnaces have been modified continuously. Here are four possible ways (Toulouevski and Zinurov, 2010):

- a water-cooled lance fitted with multi-hole nozzles blows oxygen from the top. This is named top blown steelmaking.

- as the oxygen is blown from top the bath is gas mixed at the bottom. This is termed combined top blowing and bottom stirred steelmaking.
- duplex blowing or hybrid blowing is when oxygen is blown from top and bottom simultaneously
- oxygen may be blown from the bottom only and the procedure is called bottom blown steelmaking.

As technology keeps improving, better energy utilisation and environmental sustenance is expected to remain the target.

2.4 Research Methodology

2.4.1 Literature Survey

The opening step in growing a body of knowledge essentially starts with probing preceding works to comprehend what has been done in the field of interest (Kumar and Phrommathed, 2005). In this research the researcher used the Internet access systems at the University of Zimbabwe and University of Johannesburg libraries to search for books, journals, articles and reports. The keywords used in the searching for literature were: greenhouse gas emissions, steel industry, emission mitigation, calcination, cupola furnace slag and the like.

2.4.2 Industrial Survey

The major motivation of this survey was to define the current state of affairs. The main distinguishing mark of this technique was that the researcher cannot control the variables; she can only present what has happened or what is happening (Kothari, 2004). The survey was expected to explore the strategies, tactics and practices that the companies in the steel industry are currently implementing, and other improvements needed in order to ensure economic, social and environmental sustainability. These companies included a parastatal that produces steel from its basic elements (blast furnace way), and a number of other companies that produce steel from scrap (electric furnace way) and uses the steel to manufacture steel products. The industrial survey was mostly carried out by site visits. These visits were for observation and interviews. Through observations gas emissions into the atmosphere were observed and any physical strategies put in place to manage these emissions visualised too. Key personnel were interviewed face to face and a questionnaire was used as a follow-up to the interviews. The results were evaluated for the key personnel to share ideas away from a conference room set up. From this, strategies to improve industry sustainability, manage the greenhouse gas emissions and encourage environmental sustenance were formulated.

2.4.3 Experimentation

A hypothesis was formulated from literature and industrial surveys. This was on methods of contributing towards environmental sustenance. It was researched on much further right up to experimentation in order to confirm or dispute it.

2.4.4 Triangulation

Triangulation is the use of more than one technique in a research in order to better the quality of the ensuing results. The mixing of data types, known as Data Triangulation, requires the gathering of data through several sampling approaches, so that portions of data at varied times and social conditions, as well as on a variety of people, are brought together (Bryman and Bell, 2014). The mixing of methodologies such as use of survey data and interviews is a more philosophical type of triangulation (Olsen, 2004). This form of Triangulation is what was used in this research. The researcher collected data through industrial surveys, interviews and questionnaires. A hypothesis was formulated and tested.

In order to clearly show how the research was carried out, the work was divided into different chapters. Chapter 3 delved into the industrial survey that later developed a hypothesis and an inquiry on environmental sustenance. Chapter 4 defined the hypothesis and recounted the experiments that were carried out to verify it. Chapter 5 responded to the inquiry, that came from the industrial survey, on how to make calcination process more environmentally friendly. Individual literature review was carried out for each of the chapters 3, 4 and 5.

Chapter 3

INDUSTRIAL SUSTAINABILITY IN A SHRINKING ECONOMY: THE ZIMBABWE STEEL INDUSTRY

3.1 Introduction

3.1.1 Background

The economy of Zimbabwe has fluctuated over the years. In the years 2006 to 2008 it hit rock bottom. In 2009 the introduction of a multicurrency system seemed to improve the economy amid numerous economic challenges resulting from the unending socio-political, regulatory and infrastructural shortcomings. This lead to the dissolving of some financial institutions. Furthermore, the pressure on indigenization and uncertainty of polices present a peril to economic growth and this has brought instability in the country's economy (Ndlovu, 2013). The aim of this study is to investigate and propose strategies of enhancing sustainability of steel making companies in Zimbabwe. The study was based on oral interviews and a follow up questionnaire. Information was collected from thirteen of the steel companies that are still operational and willing to participate in the survey. The rationale for picking the steel industry was that it was going to give a general reflection of the whole industry and more so involve the issues of environmental sustainability that are required when steel products are being made. The study explored raw materials and energy usage, types of energy used, and more importantly possible ways of working towards greener manufacturing. The findings show that most importantly policies need to be improved in order to attract more foreign and local investment and banks need to make their loan terms friendlier to the companies in order for them to be able to run their businesses while paying back the loans.

3.1.2 Research Motivation

The aim of this research was to find out from the actual steel companies what the main challenges in the country are, from the point of view of steel production. Then identify possible solutions, especially what the companies are able to do amid the country's economic instability. The information having been collected anonymously it was then shared with all the companies allowing each to pick what is applicable to them in order to have a measure of manufacturing sustainability.

3.2 Literature Review

3.2.1 Sustainability

Sustainability has been defined in various ways. In 1987 the Brundtland defined sustainability as the advancement that suffices the needs of the present and does not compromise the capability of future generations to meet their needs (Brundtland, 1987). Altwegg et al., (2004) mentioned the environmental, economic and social resources as three pillars that explain sustainability. These three are the pillars of sustainability that were previously presented as actual pillars as shown in Figure 3.1 or as overlapping circles shown in Figure 3.2:

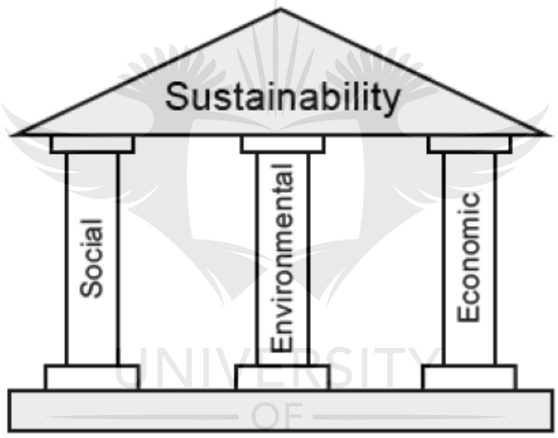


Figure 3.1: The three pillars of sustainability (Thatcher, 2015).

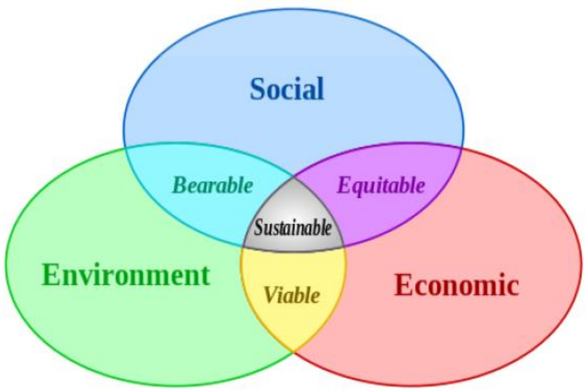


Figure 3.2: The overlapping circles of sustainability (Thatcher, 2015).

The idea behind the three pillars is that for full sustainability to occur all three pillars of sustainability must be achieved. *Environmental sustainability* looks at maintaining renewable resources, keeping pollution at a minimum and effecting reduction in the use of non-renewable resources. *Economic sustainability* is being able to sustain a specific level of economic production for an indeterminate period. *Social sustainability* of a country is being able to function at a specific level of social well-being of its people for indeterminate time (Thatcher, 2015). The circles in Figure 3.2 give the impression that some parts of Social sustainability are affected by Economic sustainability and Environmental sustainability, and vice versa. The same is the case between Environmental and Economic factors. In order to express this better Mitchel, (2000) developed concentric circles. This model shown in Figure 3.3 was well presented by Thatcher, (2015).

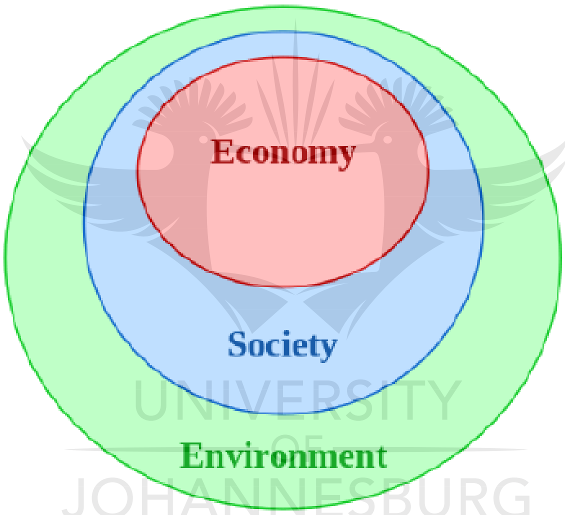


Figure 3.3: The concentric circles of sustainability (Thatcher, 2015).

The biggest circle represents Environmental sustainability which contains Social sustainability, which in turn contains Economic sustainability. The use of concentric circles is an improvement of the overlapping circles model as it underscores the fact that each circle is guarded. The growth in the economy is limited by the society and the growth of the society wholly depends on natural resources available.

In Zimbabwe, economic instability has affected sustainability as a whole. Once companies are struggling economically then Environmental and Social sustainability become the least of their worries.

3.2.2 Production of Steel in Zimbabwe

There are two main methods in which steel is produced in Zimbabwe:

A. from its elements (the blast furnace way)
B. from scrap (the cupola furnace way) (Gudukeya and Mbohwa, 2015)

3.2.2.1 Steel Production from its Elements

In Zimbabwe a single parastatal, ZISCO, was the greatest producer of steel made from its elements. It has since suspended operations because of financial constraints. Several steel businesses still functioning rely upon reusing scrap. On the visit to ZISCO key personnel described how steel was made and demonstrated a few measures that were set up to clean the gases of greenhouse emissions before releasing them into the atmosphere. Distribution of real images was not permitted by the parastatal. Nonetheless, from the visit, process flow diagrams were provided as shown in Figure 3.4 (Gudukeya and Mbohwa, 2015).

The Iron Plant

The procedure begins at the coke furnaces; it is well illustrated in Appendix 3.1. As coal carbonisation occurs, gas that has greenhouse gas in it is emitted in two ways:

- during combustion of coke furnace gas or blast furnace CO, CO_2, SO_x, NO_x, and minute levels of other elements are discharged into the atmosphere.
- during the process of converting coal to coke raw coke furnace gas $C_{10}H_8$, C_6H_6, Tar, NH_3, HS_2, HCN and other minute elements. The raw coke furnace gas is then cleaned recovering Ammonia, Crude Benzol and Naphthalene.

The blast furnace has a gas cleaning procedure illustrated in Figure 3.4

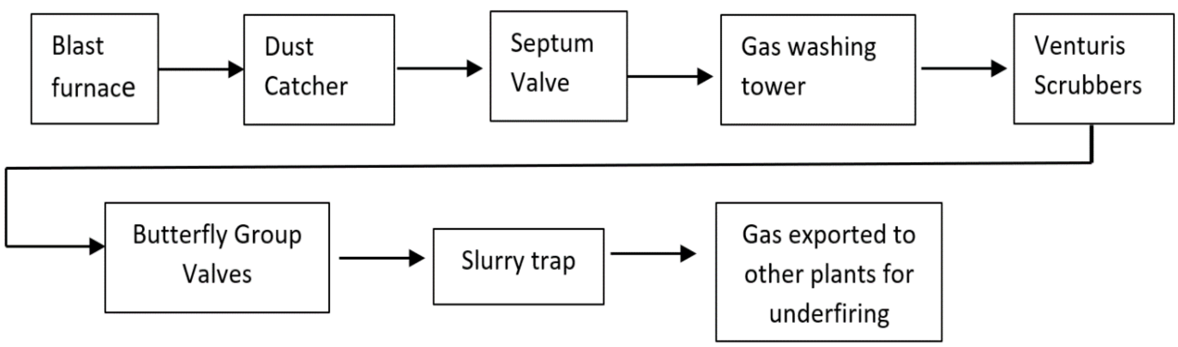


Figure 3.4: The gas cleaning process in the Blast Furnace (Gudukeya and Mbohwa, 2015)

Coke under 20mm formed at the coke plant is taken to the sinter plant. Sintering is a pre-treatment phase in the making of iron, where tiny fragments of iron ore and in a few cases, secondary iron oxide wastes such as gathered dusts and flaky surfaces of hot rolled steel, are lumped together by burning. Accretion of the fires is important to allow the entry of hot gasses as the following blast furnace process takes place. During sintering tiny particles of coke, iron ore with flux and coal are also heated to create a semi-liquid heap that hardens into permeable fragments of sinter with the size and strength properties required for adding into the blast furnace. The hardened sinter is then crushed into smaller pieces and is cooled in air. Pieces not in the correct size range are taken out through a screening process; oversized pieces are sent back to the crusher, and undersized ones are recycled in the procedure. This is shown in Figure 3.5.

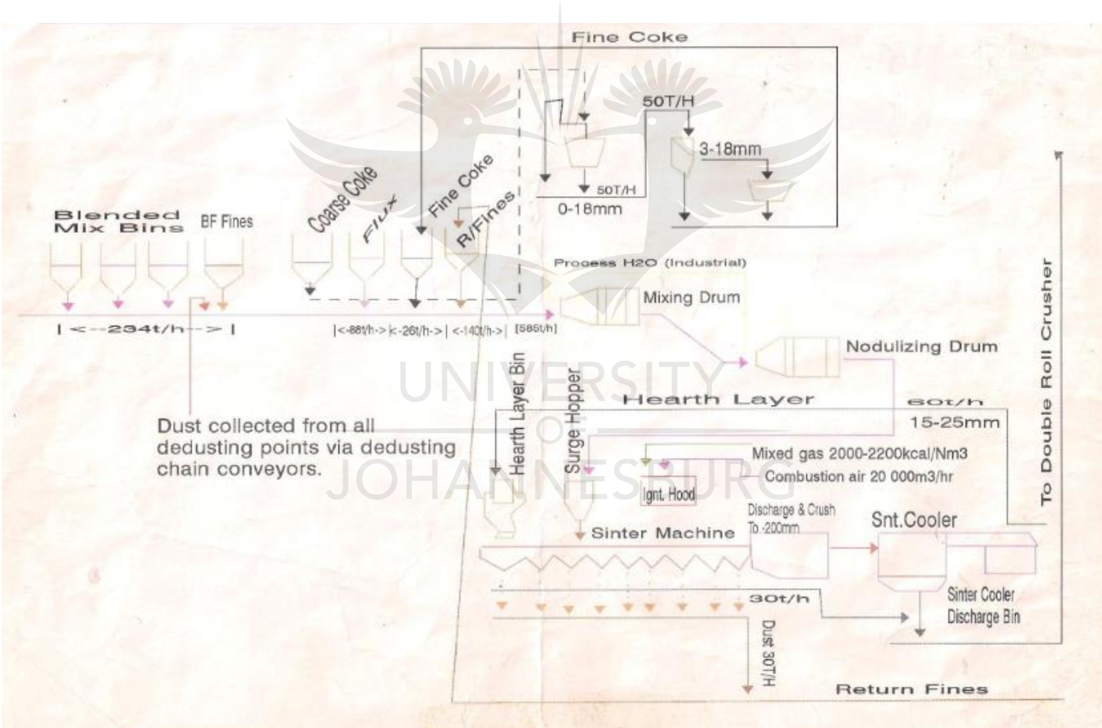


Figure 3.5: The Sinter Plant process flow chart (Gudukeya and Mbohwa, 2015)

Discharges from sintering are largely from materials-handling processes, which end up in dust going up in the air, and from the burning reaction on the component. Combustion gasses from the component reaction contain dust collected straight from the component together with combustion products, like CO, CO_2, SO_x, NO_x, and small discrete material. The level of dilution of these elements differs with the nature of the fuel and raw materials utilized and the burning conditions. Discharges going into the atmosphere comprise unstable mixes of compounds made of carbon produced in the coke draught, produced from materials made of carbon under certain conditions. Metals are evaporated from the raw materials utilized, and corrosive vapours are produced from the halides in the raw materials. Burning gasses are regularly cleaned in electrostatic precipitators (ESPs), which fundamentally decreases dust discharges; however, this has insignificant impact on the vaporous discharges. This cleaning procedure is as shown in Figure 3.6.

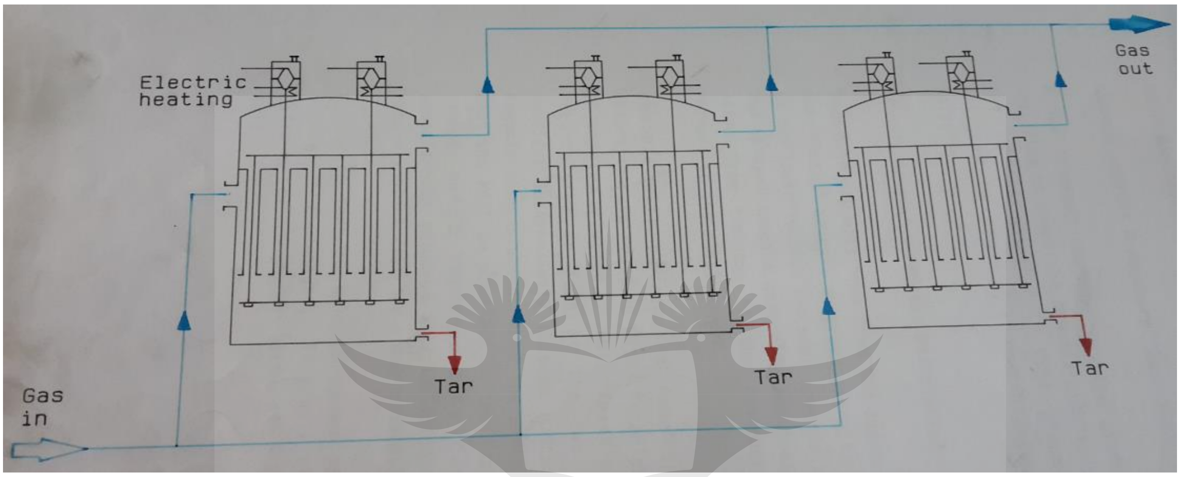


Figure 3.6: the cleaning of combustion gases in electrostatic precipitators (Gudukeya and Mbohwa 2015)

From the Sinter plant the following phase is the Iron plant. The comprehensive procedures in the Iron plant are in the Appendix 3.2 and the summary is as shown in Figure 3.7.

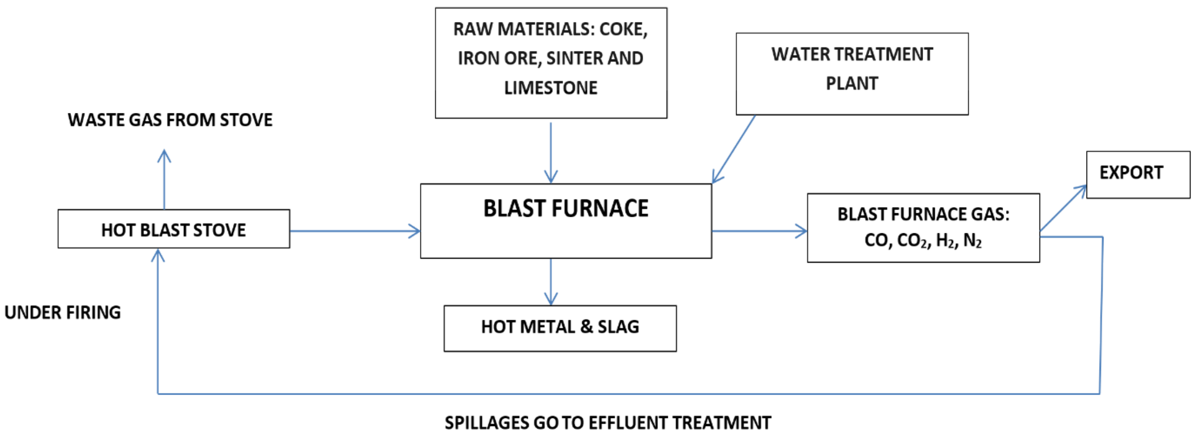


Figure 3.7: Summarised process of the Iron Plant (Gudukeya and Mbohwa, 2015)

The Steel-making Plant

From the iron plant the hot metal is transported to the steel making plant. Steel making encompasses the transformation of pig iron into steel. This is accomplished by decreasing the amounts of manganese, silicon, phosphorus, carbon and sulphur. This lessening is carried out through oxidation. The decrease levels are as illustrated in Table 1:

Table 3.1: Reduction levels of different elements (Gudukeya and Mbohwa, 2015)

ELEMENT	FROM (%):	TO (%):
Carbon	4.25	0.07
Sulphur	0.05	Nearly zero
Phosphorus	0.12	Nearly zero
Manganese	0.80	0.20
Silicon	0.05 – 0.09	Nearly zero

Molten pig iron gets to the steel making plant at 1250^{o}C having been drained from the blast furnace at temperatures over 1450^{o}C. It is stored in three immobile hot metal blenders. Two of the blenders carry up to 800 tons each and the third up to 500 tons. The hot metal blender temperature is kept at 1250^{o}C utilizing coke furnace gas. The blenders additionally homogenize chemical differences of hot metal lots. Hot metal is moved from the blenders to the basic oxygen furnace utilizing 60-ton ladles. There are two basic oxygen furnaces each with a limit of 60 tons. In the event that sulphur is high the hot metal is initially taken for desulphurisation where the sulphur levels are lessened to 0.05% or less before being added into the basic oxygen heater. Limestone, $CaCO_3$, is excavated and pulverized to 80mm size before it is transported to the lime producing plant on conveyor belts (Gudukeya and Mbohwa, 2015). The limestone is treated in shaft furnaces named lime kilns. The procedure includes calcination of limestone utilizing coke. Limestone and coke are added into the kiln from the top and air is blown from the lowest point. The heat provided by the consumption of coke forces out the carbon dioxide in the limestone producing lime following the reaction as shown in Equation 1:

$$CaCO_3 + Heat = CaO + CO_2 \qquad \text{……………………………}\textbf{Equation 1}$$

Lime lands at the lowest point of the kiln at near 40°C. At that point it is pulverized to 30-50mm size before it is transported to the basic oxygen furnace where it is utilized in the production of steel. Scrap and hot metal are added into the basic oxygen furnace and oxygen is gusted into the furnace. Lime is added about 6 minutes into the gusting. The charge weighs about 58 – 65 tons and scrap about 15 to 25% of the full charge dependent on hot metal chemical analysis. The oxygen gusting lessens the carbon content in the hot metal to amounts needed in steel following this exothermic reaction in Equation 2:

$2C + O_2 = 2CO$ ………………………………….**Equation 2**

Lime collects the oxides produced during steel making. All the merged oxides are called slag. Silicon is the primary constituent of the slag. It is acidic and will thus react with lime which is alkali. Sufficient lime is added to make the slag alkali and is equipped to eliminate undesirable components as the steel is being produced. The proportion of CaO to SiO_2 is called alkalinity and an estimation of 3.0 is the standard slag alkalinity utilized. A bit of the iron is oxidized and becomes a part of the slag. As the oxygen is gusted, silicon and manganese are additionally oxidized as shown in Equations 3 and 4:

$Si + O_2 = SiO_2$ …..**Equation 3** and $2Mn + O_2 = 2MnO$ ……**Equation 4**

These oxides are held in the slag produced as the lime was added. Some sulphur is expelled as sulphur dioxide as in the reactions shown in Equations 5 and 6:

$MnO + FeS = MnS + FeO$ …..**Equation 5** and $FeS + Mn = MnS + Fe$ ….**Equation 6**

More sulphur reacts with manganese and infiltrates the slag as sulphides of manganese as per reactions in Equations 7 and 8:

$MnO + FeS = MnS + FeO$ …..**Equation 7** and $FeS + Mn = MnS + Fe$ …..**Equation 8**

Phosphorous enters the slag as a composite of the oxide and lime and the reactions that take place in the slag containing iron oxides are as shown in Equations 9 and 10:

$4P + 5O_2 + 8CaO = 2(CaO)_4(P_2O_5)$ ……**Equation 9**

$4P + 5O_2 + 6CaO = 2(CaO)_3(P_2O_5)$ ……**Equation 10**

As silicon and manganese react with oxygen the reactions are extremely exothermic, and the heat produced increases the temperature to 1650°C required for steel making. Since so much heat is produced it becomes imperative to add on scrap as a coolant to regulate the temperatures. The gusting of oxygen lasts about 20 minutes and, in this time, the required temperature of 1650^{o}C would have been accomplished. In the event that the temperature is under 1650^{o}C oxygen will be blown again to raise it to the required temperature.

At the point when oxygen gusting is finished the temperature is determined and tasters are collected for chemical analysis in two ways:

1. Bath analysis: Steel tester for steel examination
2. Slag analysis: Slag tester for slag examination

When the steel reaches the required characteristics, it is drained into a ladle. As the draining is occurring de-oxidants are added to the ladle to expel diffused oxygen. Components that are needed to meet steel description are likewise supplemented. To meet the carbon requirements coke is added and ferrosilicon and ferromanganese are supplemented too to meet silicon and manganese requirements individually. The steel produced is 91.2% of the initial charge. At this stage, steel is ready for next processes such as casting; however, many characteristics require that it initially passes through the ladle furnace. At the ladle furnace the temperature is elevated to the essential casting temperature and thoroughly mixed. Chemical specifications of the steel are also perfected. The carbon dioxide that is created while gusting is discharged as carbon monoxide or carbon dioxide vaporous. The steel making procedure is outlined in Figure 3.8. This procedure demonstrates a few measures set up to clean the gasses before they are discharged into the atmosphere. Sometimes, greenhouse gasses are simply discharged into the air without any filtering processes.

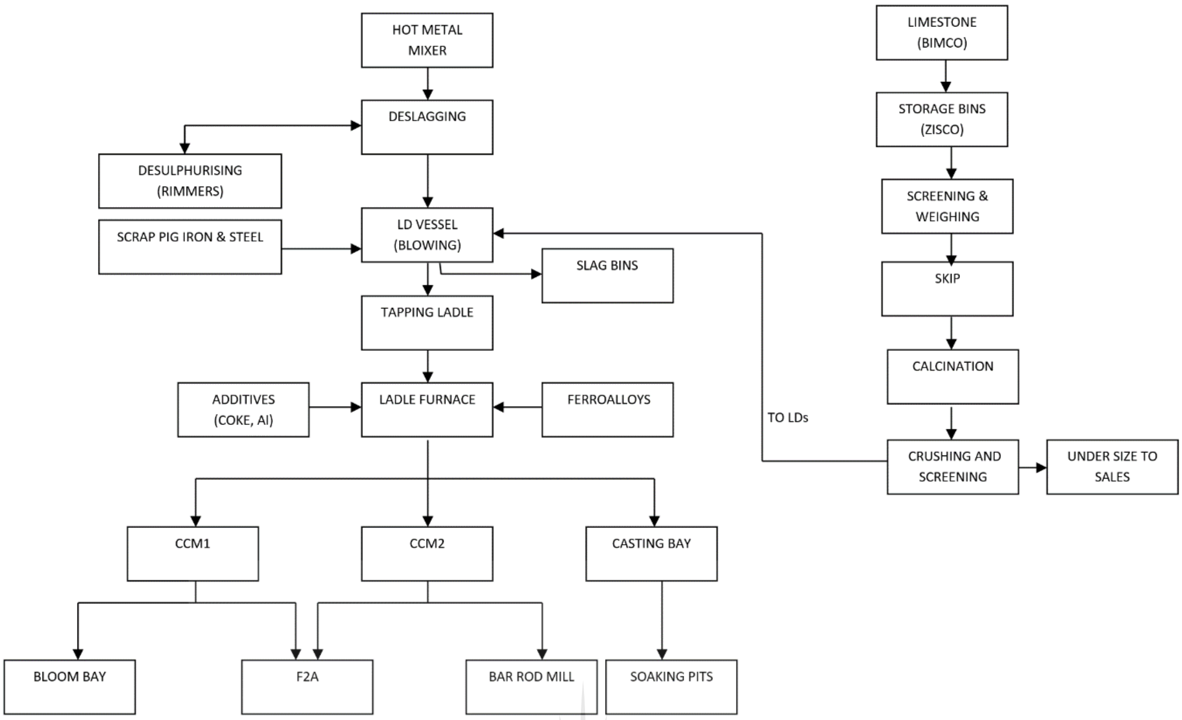


Figure 3.8: Steel making flow chart (Gudukeya and Mbohwa, 2015)

(LD is the Basic Oxygen Furnace, similarly known as Basic Oxygen Vessel or Basic Oxygen Converter. LD is shortened form for Linz-Donavitz which are two towns where this steel making process was created. CCM1: Continuous Casting Machine 1. CCM2: Continuous Casting Machine 2. Steelmaking ends with casting.)

3.2.2.2 Steel Production from Scrap

Other companies reuse steel from iron and steel scrap. This reutilizing of scrap is very common. The most important raw material supplied to such companies is scrap, and its ready availability is synonymous with the high casting production that is continuous. Many of these companies have scrap recycling sections or auxiliary scrap businesses as a way of controlling raw material expenses, an imperative issue since they almost completely rely on scrap as their raw material. Generally, recycling in this industry worldwide is over 70% and still growing (Pehlke, 2001). Manufacture of steel and its products from scrap as depicted by one of the companies that utilise scrap is outlined in Figure 3.9. This recycling is achievable because steel can be multi-cycled and reproduced into new items while preserving its original properties (Estrada et al., 2012). Other different materials may only be reused into a lower-quality items. In this way steel is the only true cradle-to-cradle material. Figure 3.10 demonstrates this cradle to cradle life cycle of steel.

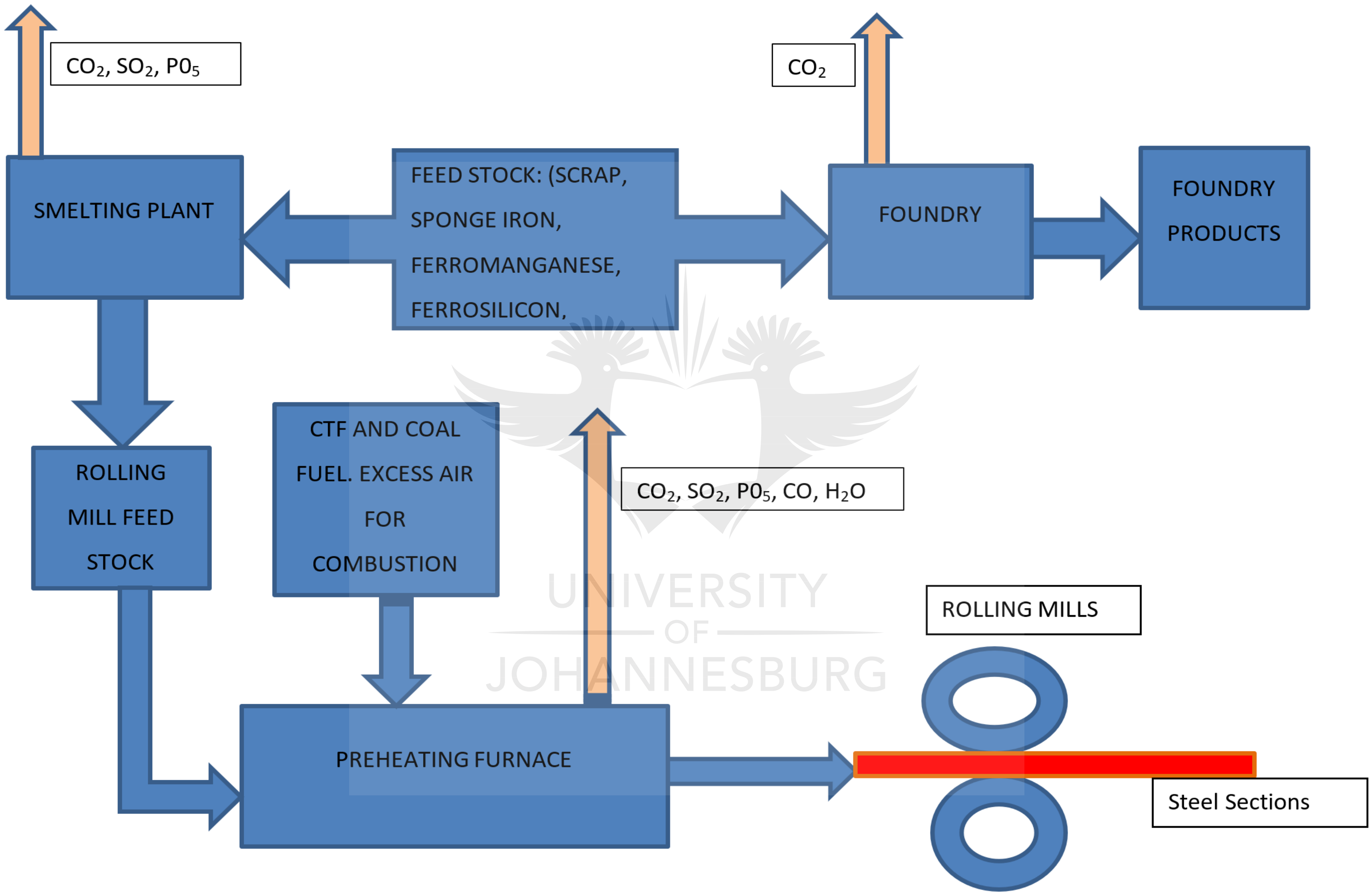


Figure 3.9: Production of Steel products from scrap (Gudukeya and Mbohwa, 2015)

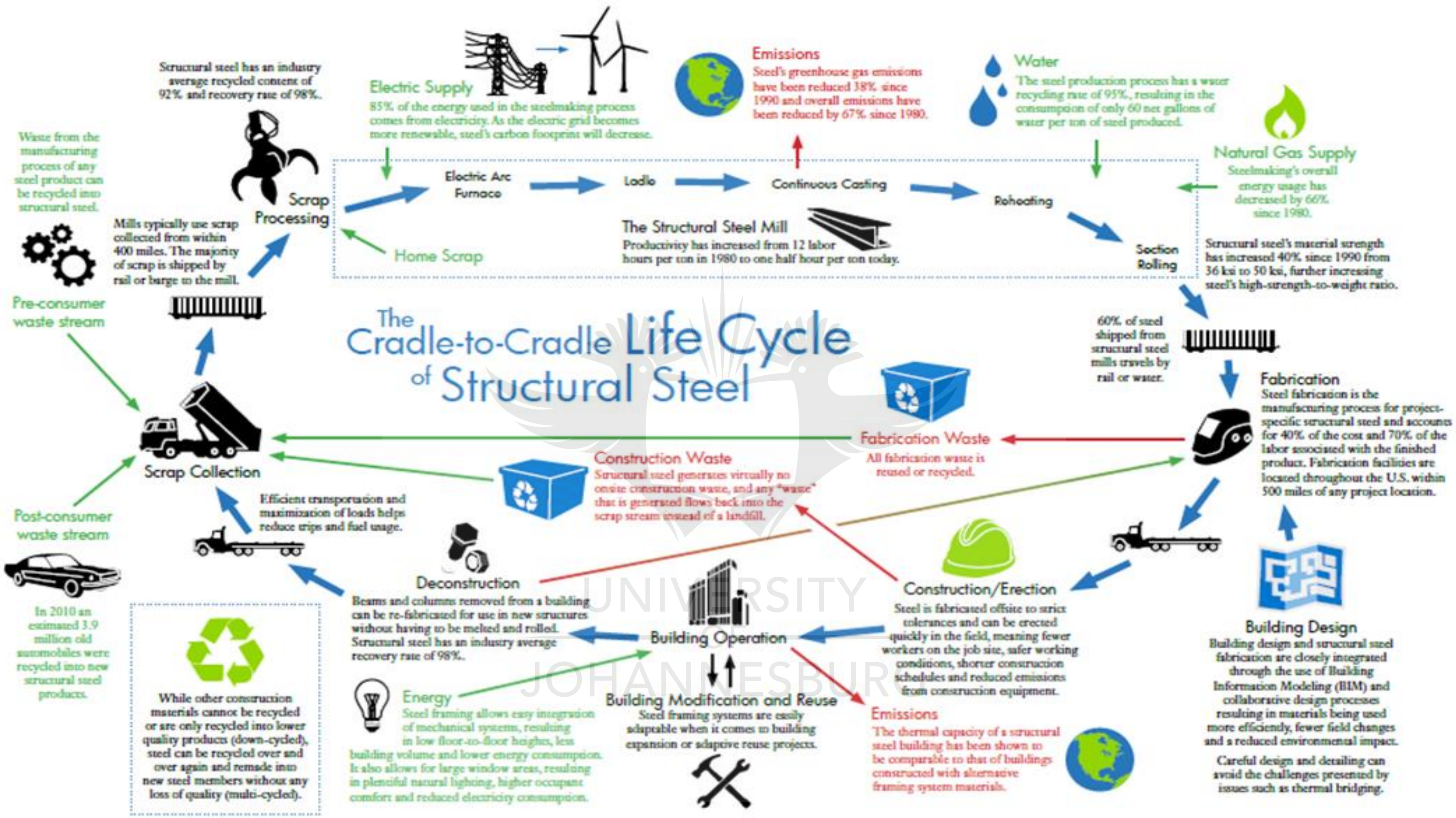


Figure 3.10: Cradle to Cradle life cycle of steel (AISC, 2017)

3.3 Research Method: The Delphi Approach

To develop the assessment of the sustainability of the steel industry and to help co-create improvement factors for the industry, the Delphi approach was used. RAND Corporation developed this method in the 1950s as a method for deriving a harmonious view from a group of experts (Gough, 2008). This method was initially developed for military uses, but it has since been used extensively in a wide range of forecasting and decision making. The rudimentary principle is that experts in a specific field are individually given a set of questions. Then their answers are compiled and presented back to them, usually anonymously. They will then have an opportunity to revise their responses / opinions basing on the results or the compilation of responses from fellow experts. With this, they are able to apply the more comprehensive approach in their individual companies. The key features of the method are reflexivity - an attitude of attending systematically to the context of knowledge construction, and a degree of anonymity. The progression is intended to deliver results that filter the combined knowledge of experts in a field, free from the influences that may come about if they are brought about in a conference-like set up (Gordon, 1994).

The Delphi method is characterised by four key features (Rowe and Wright, 1999):

1. Anonymity of Delphi participants
2. Iteration in the process
3. Controlled feedback
4. Statistical combination of group response

Where the group is homogenous, then a smaller sample of ten to fifteen people may bring in adequate results. However, if heterogeneous groups are involved (e.g. an international study), then a bigger group of participants will be required and hundreds of participates might then be required (Skulmoski et al., 2007).

3.3.1 Study Details

This industrial sustainability study was based on an oral interview of thirteen companies to define the parameters of the study, the main issues to be investigated and a follow up questionnaire to study a wider set of companies based on the initial parameters. Information was collected from thirteen of the Steel companies that are still operational in the Steel industry of Zimbabwe. The rationale for picking the Steel industry was its significant impact on the Zimbabwe economy, potential for export and high energy intensity of the industry and its significant relevance to environmental sustainability and industrial emissions. The study explored raw materials and energy usage, types of energy used, and more importantly possible ways of working towards greener manufacturing.

3.4 Application of the Method

For this study the Delphi approach was used. Experts from the required Steel industry were initially identified and requested to participate in the investigation. Thirteen companies agreed to participate in the study and agreed to the first round of the Delphi approach that was the oral interview. All of the companies were dealing with sourcing of scrap metals and producing steel products and this produced a homogenous sample and thirteen respondents were sufficient.

The initial contact of the nominated companies was done on the phone. Companies were told about the research and were invited to participate in an oral interview. They were assured of anonymity in the sense that none of their statements were to be attributed to them by name. Individuals, the industry experts, were then identified to represent each company in the oral interviews. Appointments were set at their convenient time and the researcher went in with open ended questions. Open ended questions allowed the researcher to get even more relevant information. The theme was on what challenges the companies were facing and how financial and environmental sustainability might be achieved. These experts representing each company included technical representatives of the different Steel/Metal companies who all have engineering backgrounds such as foundry forepersons and managers, workshop and plant managers. In some cases, however, the actual individuals were not the technical people, they were Accountants or Marketing personnel, but when it came to the technical questions they referred to the technical individuals in the company and allowed the researcher access into their foundries to see how the work was done and meet the technical people on the ground. To preserve anonymity pictures were not taken in the foundries.

Using the information and key factors suggested during the oral interviews, the questions were then refined by the researcher and the study pursued through a questionnaire in the second round. At this point one company never got to fill in the questionnaire so the sample size reduced to twelve in the second round. The reasons were mainly individuals feeling that they had done enough in the oral interviews, so they did not really have to take more time out of their busy schedules to do the questionnaire.

In the questionnaire, participants were asked to briefly describe the profile of their companies and then answer questions on the following:

1. The highest qualification of the participant
2. Select the level of his or her position in the company from the three levels provided
3. Identify the number of employees in the company
4. Identify the main raw materials used and how they are acquired
5. In US$ specify how much is spent on energy (electricity, gas or coal) and water at full capacity and at current capacity.
6. Specify the main products/s and the target market
7. The current capacity that the company is functioning at
8. State the company monthly turnover in US$ at full capacity and at current capacity
9. Based on the oral interviews a list of eight challenges facing the industry was generated, participants were then requested to show to what degree each had affected their company. Space was provided for each of the company to add any other challenges not specified in the list already
10. Also based on the oral interviews, five possible solutions to make the Zimbabwe steel/metal industry do well in the long term were presented and participants had to indicate to what level each of the possible solutions would actually assist their company's sustainability
11. Identify the number of pollution control mechanisms in place
12. Coming from the oral interviews thirteen factors that influence environmental sustainability were stated and participants had to indicate to what level each of the factors was being applied

13. Lastly, space was provided for participants to add a process flow diagram/s for their companies, especially indicating strategies or devices in place for pollution control

3.5 Results

Below is the summary and analysis of the responses from the 12 companies. All the questionnaires are attached in the Appendix. In a few cases where questionnaires were not completed in full more phone calls were made to add the answers so the print or handwriting may differ from the original in these few cases.

For the first and second questions that indicated the highest qualification and position in the organisation of the respondent representing each company the results are shown in Table 3.2 and Table 3.3:

Table 3.2: Degree qualifications of respondents

Highest qualification	Certificate	Diploma	HND	Bachelors	Honours	Masters	PhD
	2	2	2	2	3	1	

Table 3.3: Position of respond acts in the company

Position in organisation (select one)	Number
Top Management: Executive / Senior management/ Managing Director/Other specify	3
Middle Management: Project Manager/ Plant Engineer/ Production Manager/Other specify	5
Operational staff: Engineer / Foreman/Journeyman/Operator	4

The results show an almost equal distribution on the levels of the highest qualifications and position in an organisation of the specific respondents. This however did not affect the results because all respondents ideally consulted with different relevant departments in filling in the questionnaire. The specific individual used by each organisation to fill in the questionnaire largely depended on the size of the company. In small companies, people in the top management filled in the questionnaires, in big companies the middle management was used and operational staff was used in 1 big company. The general sizes of the companies measured by the number of employees is shown in Table 3.4

Table 3.4: Approximate number of employees in the organisations

< 10 employees (Micro business)	< 50 employees (Small Business)	< 250 employees (Medium Sized)	More than 500 employees
	3	8	1

The raw material that is common to all the companies is scrap metal. This is mostly purchased from local vendors and mines. Other main raw materials are ferro-alloys, pulverised coal and gases and are all purchased locally. With the current state of the country's economy all the companies are not functioning at their individual full capacity. So, a question was asked for the companies to state at what capacity they are currently functioning at. Three companies (labelled 4, 5 and 6) were not at liberty to disclose monetary details hence it was not possible to clearly determine their current functional capacity. Table 3.5 shows the individual current capacity and the average capacity which well represents the current steel industry general capacity.

Table 3.5: The individual company current average functioning capacity

Company	Current functioning capacity %
1	60
2	27
3	45
7	15
8	50
9	40
10	15
11	25
12	30
Average	**30.8**

Data on continuously-cast steel output for the years 2013 to 2015 for three countries in Europe and two top African countries was acquired from World Steel Association (WSA, 2016). This served as an indication on the capacities at which other steel industries in the world are operating. Table 3.6 shows the data.

Table 3.6: Average functioning capacity of other steel industries in the world (WSA,2016)

Country	% Crude steel output			
	2013	2014	2015	Average
Belgium	100.0	100.0	100.0	100.0
Italy	95.0	94.2	94.3	94.5
Spain	97.8	97.8	98.2	97.9
Egypt	100.0	100.0	100.0	100.0
South Africa	99.7	99.5	99.4	99.5

Figure 3.11 shows a comparison of the functioning capacity of the Zimbabwean steel industry to other steel industries. The other industries are all operating at nearly 100% capacity while the Zimbabwean industry is struggling at about 31%. This shows how important it is to look at sustainability means if the industry is to survive.

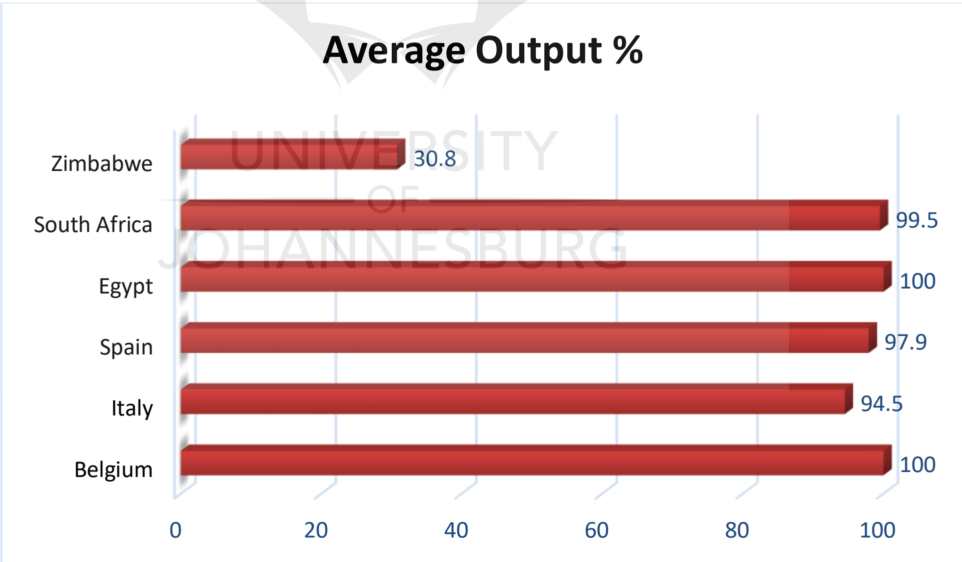


Figure 3.11: Comparison of the functioning capacities

Data on how much is spent on energy and water bills was collected as well. The main sources of energy for the companies are electricity, coal and gas. Table 3.7 and Figure 3.12 show this data comparing the expenses at full capacity and current capacity.

Table 3.7: Comparison of monthly expenditure on electricity cost at full and current capacity

Company	Electricity ($)	
	Full Capacity	Current Capacity
1	2 500	1 500
2	270 000	70 000
3	60 000	20 000
7	1 600	500
8	9 000	5 000
9	60 000	18 000
10	70 000	22 000
11	60 000	18 000
12	200 000	25 000

Companies 4, 5 and 6 did not supply this data. Companies 3, 8, 9, 10, 11 and 12 do not have water bills because they have boreholes at their properties and use that water for their work. This is a good way of saving on resources expenditure as the water expense is only at the start when the borehole is drilled. After that the only expense associated with water is the electricity in the event of a pump being used. This is cheaper than using city water and the bill is added to the electricity bill.

Companies 1 and 2 have water bills of $500 and $40000 respectively at full capacity and $300 and $15 000 respectively at current capacity. The water bill for company 7 is the same at full and current capacity at $80. Only two companies used coal as a source of energy in addition to electricity. The cost of coal at full capacity for companies 1 and 2 respectively are $60 000 and $80 000 while at current capacity $40 000 and $20 000. Company 11 uses gas in addition to electricity. The cost at full capacity is $10 000 and currently $4 000 as shown in Figure 3.12.

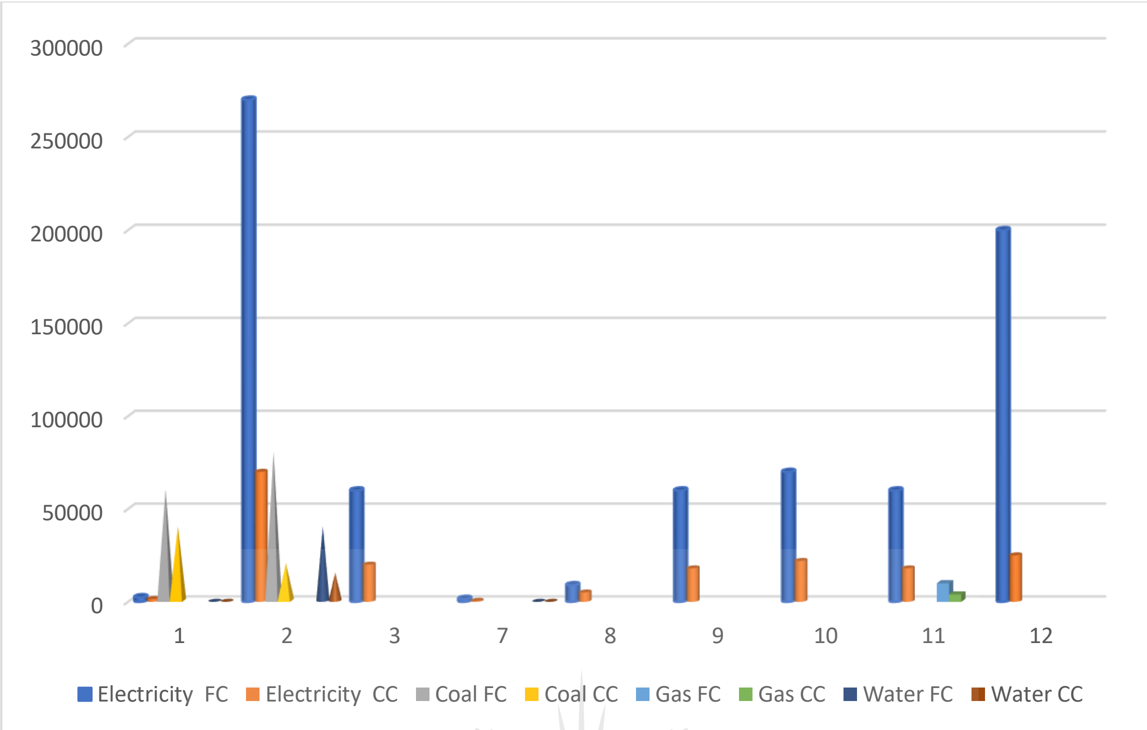


Figure 3.12: Expenditure of energy and water at full and current capacity

Electricity costs dominate the costs of any other energy inputs in almost all the companies. Only company labelled 2 is where the cost of electricity is less than that of coal. So, the availability and affordability of electricity are key factors for industry in Zimbabwe.

The next section in the questionnaire looked at the challenges that the whole industry is facing and the possible solutions. The initial interviews generated eight challenges and five possible solutions that were revealed in the questionnaire. The respondents were presented with this list of challenges from the pilot study and then asked to indicate the extent to which each of the factors has affected their organisation. The results are shown in Figure 3.13.

Figure 3.13: To what extend each of these factors are affecting the organisations

Cash shortage and import and export policies proved to be the biggest challenges for all the companies. However, the other six are affecting business badly too since the lowest percentage agreeing that a challenge is affecting each company is 73%. The respondents had to also indicate to what extent they agreed with possible solutions. The results are shown in Figure 3.14:

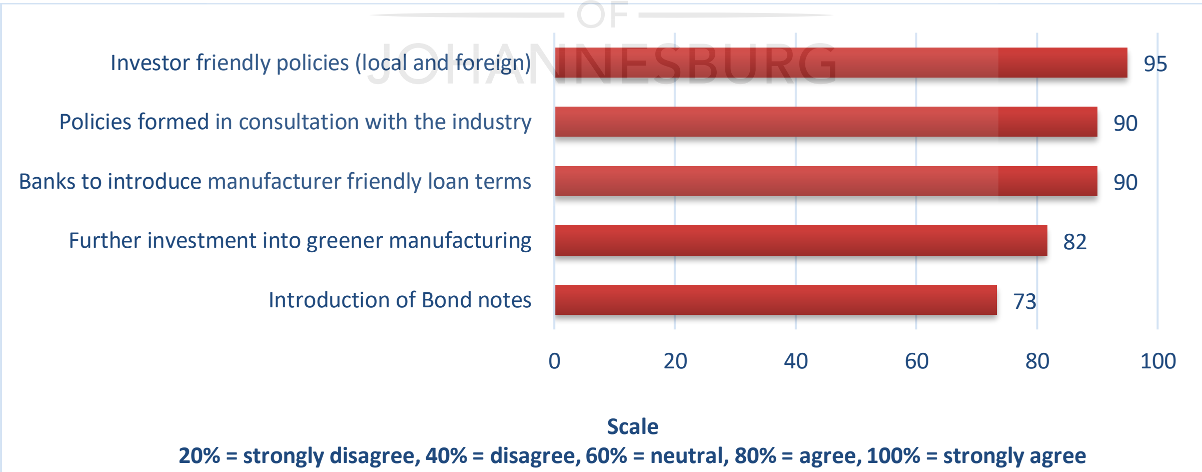


Figure 3.14: To what extend would each of these help sustainability

The results show that almost all companies agree unanimously that improvement of the investor policies, both local and foreign, would increase chances of sustainability. The lowest agreement percentage is 73% in this case too, indicating that the other four proposals would certainly go a long way towards sustainability.

These results point to the fact that most companies are in agreement with the suggestions that came out of the initial interviews. There is one company that strongly disagreed with the introduction of Bond notes as a possible solution. This is because the company mainly deals in international business so the introduction of Bond notes that are only used locally will not alleviate its problems. But holistically what was presented here are the main challenges facing the Zimbabwean industry as a whole and the five possible solutions would assist in economic sustainability of the industry which will in turn encourage companies to improve environmental and social sustainabilities too.

Four additional points were stated in the questionnaires as possible solutions too. Looking at them closely shows that they are already cared for in the main points highlighted as follows:

1. Resuscitating the biggest parastatal that produces steel from its elements - this will be made possible by the introduction of investor friendly policies, local and foreign.
2. Adding foundry products on controlled imports – this will be cared for when policies are formed in consultation with the industry.
3. Adjusting electricity charges on companies with induction furnaces – covered when policies are formed in consultation with the industry.
4. Encouraging use of other foreign currencies in addition to the US$ - covered when policies are formed in consultation with the industry.

Of great importance too is environmental sustainability. So, respondents were asked to state how many pollution control strategies they have in place. Table 3.8 shows the results.

Table 3.8: How many pollution control strategies/devises do you have in place?

1	2	3	4	5 or more
5	4	1	1	1

It is encouraging that even in a harsh economic environment the companies have at least one mechanism in place to care for the environment. This number depends really on the individual processing of each company. They were also requested to draw a process outline of their company highlighting the areas where these mechanisms are in place. Six companies drew this and one only highlighted the mechanisms for caring for the environment in place. The other five did not, but such probing will encourage them to look into the matter and do more about it.

From the interviews thirteen factors that may influence environmental sustainability were identified. In the questionnaire the companies were asked to point out the ones that are being applied and that may be applied in their companies by strongly agreeing or strongly disagreeing. The results are in Figure 3.15:

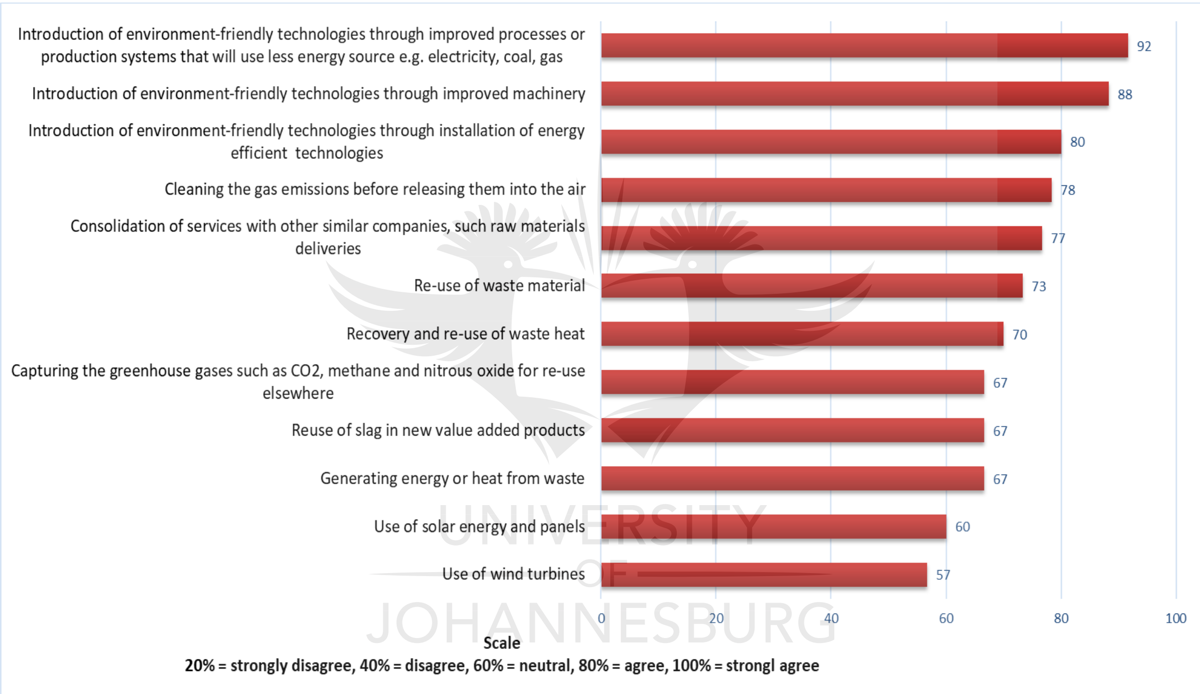


Figure 3.15: Possible pollution control mechanisms

In as much as the question was looking at the current mechanisms in place for environmental sustenance, the companies mostly responded to the positive possibility of applying these mechanisms in their processing.

In almost all the cases the companies are showing their willingness to apply different other environmentally friendly mechanisms in addition to what they may already have in place. The companies are willing to look into the mechanism more to see if it is applicable to their system. This shows that there is great potential for environmental sustainability.

3.6 Conclusion

In the final round, these results were presented, along with the extra comments made by individual participants, and a reassessment and possible implementation of new ideas was requested. Three broad objectives were accepted that each company should identify:

1. the aspects that would ensure long term sustainability of the company in a volatile economy i.e. companies were requested to identify the aspects they had not implemented and see if and how they could implement them too. For example, it was observed that companies that have boreholes in their properties have less continued water expense. Companies that are using city water may consider the option of drilling boreholes in their properties too.
2. the factors that would ensure environmental sustainability and as individual companies pick the ones they need to improve on with the benefit of regional and global recognition / compliance. A financial analysis of each of the proposed factors will help the companies to pick the feasible options.
3. if there are any channels of combining some aspects of their businesses with other companies such as combined sourcing of raw materials, combined disposal of waste in order to save funds and the environment

For planning purposes, the questions generally are of three types.

1. forecasts on the occurrence of future developments – in this case the questions centred on production and environmental sustainability
2. desirability of some future state – need for this sustenance
3. the means for achieving or avoiding a future state - ways in which sustainability can be achieved. As the ideas are exchanged each company is able to identify areas in which they can improve.

In a sense, the Delphi method became a controlled discussion. A group of experts moved toward consensus without any feelings of superiority or inadequacy. Planners reviewing these results can make judgments based on these and their own knowledge, capabilities and goals for their companies.

Since the number of respondents is typically small, the Delphi method does not (and is not intended to) produce statistically noteworthy results; in other words, the results provided will not forecast the reaction of a larger population or even a changed Delphi panel. They represent the synthesis of opinion of the specific group. The value of the Delphi method depends on the concepts it creates, both those that evoke accord and those that do not. The opinions for the extreme positions, if any, also represent a useful result (Gordon, 1994).

Chapter 4

DERIVING VALUE FROM WASTE: BLAST FURNACE SLAG AS A SOLID LUBRICANT IN DRILLING PROCESSES

4. 1 Introduction

4.1.1 Background

Manufacturing companies have to continuously look for ways to innovate, derive business opportunities and make better use of their waste streams. The value intensification for waste is a grand challenge facing many companies, especially the steel making industry.

The process that produces pig iron and cast iron also produces secondary raw materials and industrial wastes. Furnace slag is a secondary product produced in large quantities in these processes. Two types of slag are commonly produced and are named according to the type of furnace used: Blast furnace slag and Cupola furnace slag. Each of the two is created from melting of veinstone (parts of metal bearing materials), slag forming additives and coke ash. Generally, slag is made up of compounds of metallic and non-metallic oxides, elements which form solutions and chemical compounds with each other and also comprise small quantities of metals, sulphides of metals and gases. The utilisation of slag in different fields of industry heavily depends on the chemical, mineralogical and physical properties of the slag. Chemical similarity of blast and cupola furnace slag has resulted in studies focusing on the potential of utilization of cupola furnace slag in the production of concrete(Baricov et al., 2010).

Two companies in Zimbabwe: Midland Metals (Gweru) and Craster International (Harare): both manufacture steel products from scrap metal. Products that are common to the two are grinding media, manhole covers, ploughs and mining spares. Raw material is mostly scrap metal and the main processes carried out are scrap processing, mould making, casting, fettling (if necessary) and machining, as shown in Figure 4.1.

The common furnace of the two companies is the cupola furnace. The main challenge that the companies are facing now is how to dispose of the cupola furnace slag. The production of the cupola furnace slag as waste is up to about two tonnes daily. They both have slag heaps at their properties such as one shown in Figure 4.2. Midlands Metals uses some of its city council's land too to just dispose of the cupola furnace slag.

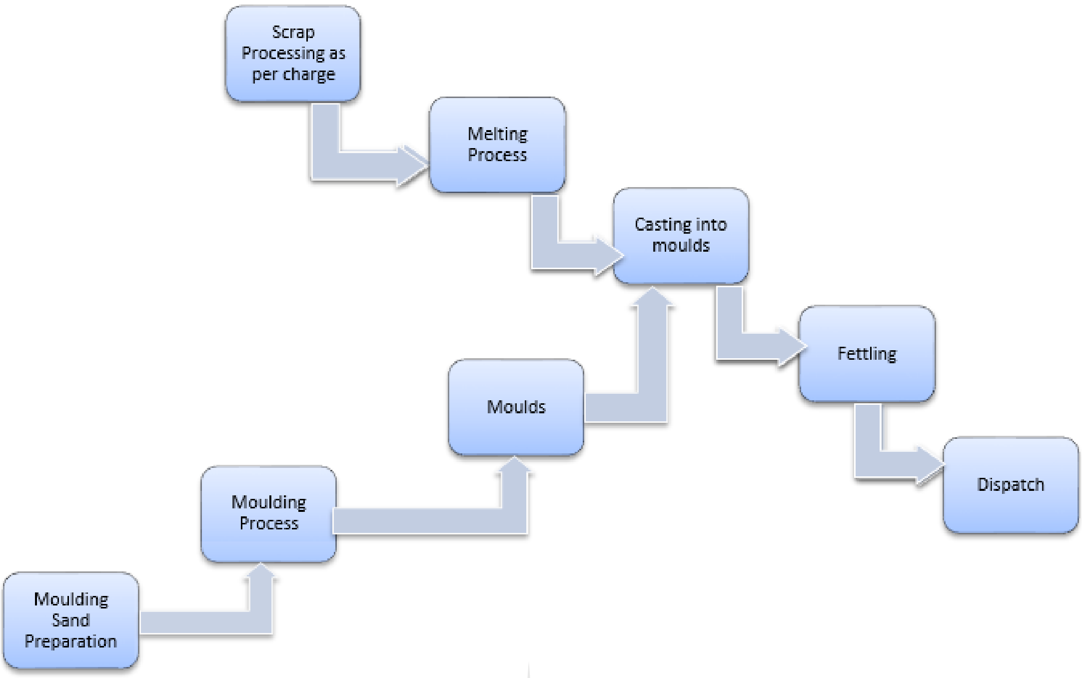


Figure 4.1: Process flow chart

Figure 4.2: Slag heap at Craster International

Both companies have the cupola furnace slag as an industrial waste and are now looking into making it a secondary raw material instead. Samples of the cupola furnace slag were collected from both companies and tested. A non-destructive analytical technique was used to determine the elemental composition of the materials. This was done at Peacocke & Simpson, a company leading in the minerals processing industry, in Harare. The full result sheet is in Appendix 4:1. The samples are shown in Figures 4.3 (a) and (b).

(a) (b)

Figure 4.3: (a) Craster International Sample and (b) Midlands Metal sample

4.1.2 Research Motivation

The aim of the research was to find ways of utilising the cupola furnace slag that is produced at both companies as waste material. The research first covered possible uses of ground granulated blast furnace slag and the results were presented in order to accommodate other parts of the industry that produce ground granulated blast furnace slag. A research on the possible use of cupola furnace slag was then carried out and further experiments to verify the possible uses that had been researched were done in order to give a concrete solution to the companies.

4.2 Literature Review

Fabrication that is carried out in a foundry is a pillar of any modernised economy. It delivers crucial raw materials to a variety of fabricating divisions, such as the automobile, mining and all-purpose engineering sectors. Among the challenges faced by foundry fabrication is the management of waste. Foundry sand, blast furnace slag and cupola furnace slag are among the main contributors to foundry waste. In South Africa alone, foundry sand waste created annually is about 375 thousand tons (Madzivhandila, 2018). A lot of research has been carried out on how to utilise foundry waste. One such research concluded that foundry sand waste can be utilised as fractional replacement for original silica sand in the fabrication of bricks or paving. This reduces the cost of producing the bricks and paving (Madzivhandila, 2018). However, in this research the challenge that is being investigated is the management of waste slags.

4.2.1 Ground Granulated Blast Furnace Slag

Ground granulated blast furnace slag is produced using blast furnace slag. At the furnace exit, liquid blast furnace slag is rapidly cooled in a water pool, or with powerful and effective water jets, forming a fine, granular, completely non-crystalline, shiny type known as granulated slag (Hwang and Lin, 1986). This slag is commonly taken to be waste in industry however it causes less environmental damage when compared to other building materials. Table 4.1 shows the chemical composition of a realistic sample of such a slag that was used in an experiment. The table contains elements with the highest percentages, up to about 97% full composition. This highlights that generally, ground granulated blast furnace slag does not contain elements that are poisonous to the atmosphere and the environment. Ground granulated blast furnace slag has about the same hydraulic capabilities as Portland cement. Once finely ground and blended with Portland cement, the mix shows exceptional cementitious characteristics (Bilim et al., 2009).

Table 4.1: Ground granulated blast furnace slag chemical composition (Bilim et al., 2009)

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
%	36.70	14.21	0.98	32.61	10.12	0.99	0.42	0.76

Under certain specific circumstances, granulated ground blast furnace slag can build up the mechanical strength of the Portland cement. This binding capacity occurs because of the presence of a hydration product called Calcium silicate hydrate. Consequently, ground granulated blast furnace slag is for the most part utilized as a replacement for some of Portland cement (Murgier et al., 2004). If the slag is allowed to cool progressively in air, it congeals into grey crystalline material known as crystallised slag. This slag is utilized as aggregates in the synthesis of concrete. The common sand is also substituted wholly or in part by the crystallised slag in the synthesis of concrete. The chemical composition of slag fluctuates according to the nature of the ore, the composition of the limestone flux, coke utilization and the type of iron being produced (Shoaib et al., 2001).

Ground granulated blast furnace slag is mostly used in concrete making by either fully or partly substituting Portland cement. Shi and others pointed out that using ground granulated blast furnace slag as a fractional substitution of normal Portland cement enhances the strength and durability of cement through the formation of a denser medium and in that way extending the life of concrete structures (Shi and Qian, 2000). Benefits of using ground granulated blast furnace slag in concrete are that:

- Concrete containing ground granulated blast furnace slag may be used at elevated temperatures (Siddique and Kaur, 2012).
- Concrete from ground granulated blast furnace slag and metakaolin as cement replacement materials have enhanced microstructure and durability (Duan et al., 2013).

Slag produced as secondary or waste materials in iron and steelmaking have been utilised as aggregate constituents in construction materials that include insulating boards, cement, concrete and bituminous materials (Pehlke, 2001). Here are some of the benefits that were found in specific researches:

- Concrete containing ground granulated blast furnace slag may be used at elevated temperatures (Siddique and Kaur, 2012).
- Enhanced microstructure and durability of concrete from ground granulated blast furnace slag and metakaolin as cement replacement materials (Duan et al., 2013).

4.2.2 Environmental Credits for Recycling Granulated Blast Furnace Slag Based on LCA

The system expansion method was used to quantify environmental benefits in an open loop recycling case. The environmental benefits of the granulated blast furnace slag recycling to raw materials for Portland cement, slag cement, slag powder and silicate fertilizer, was enumerated. The environmental credit based on the characterized impact on global warming is shown in Table 4.2.

Table 4.2: Determination of environmental credit based on the global warming impact (Lee and Park, 2005)

Item	Recycling Application			
	Raw material for Portland cement	Raw material for slag cement	Raw material for slag powder	Raw material for silicate fertilizer
Recycling of the GBFS (1)	4.3	0.1	60.0	10.9
Substituted product system (2)	871.0	875.0	809.2	154.5
Environmental credit (1-2)	-866.7	-874.9	-749.2	-143.6
Environmental credit relative to the best recycling option	99.1%	100.0%	85.6%	16.4%

The environmental credit is signified by a negative sign in Table 4.2 demonstrating decrease in the environmental loads because of reclaiming, while the positive sign shows the ecological effect that would have happened. From these outcomes, it can be observed that most extreme ecological credit of the granulated blast furnace slag reusing happens when such slag is reused as raw materials for slag concrete and Portland cement. According to the LCA outcomes main conclusions are that:

- Highest environmental benefits of the ground blast furnace slag reuse happen when reused as raw materials for slag concrete and Portland cement.
- The higher the environmental impacts of the replaced item and the lesser the environmental impacts of the reusing procedure of granulated blast furnace slag, the higher the environmental gains of granulated blast furnace slag.

Accordingly, granulated blast furnace slag should be recycled to form raw materials for slag cement and Portland cement in order to maximise the environmental credits (Lee and Park, 2005).

4.2.3 Comparison of the Cupola Furnace to Blast Furnace Slag

Cupola furnace and blast furnace slag are similar in their chemical composition, properties and nature. Figures 4.4 and 4.5 show how closely related they are in physical appearance. Their chemical compositions show the same basic oxide components as seen in Table 4.3.

Table 4.3: Range of chemical composition cupola furnace slag and blast furnace slag (Baricov, et al. 2010).

	CaO [%]	SiO2 [%]	Al2O3 [%]	MgO [%]	MnO [%]	FeO [%]
CUPOLA FURNACE SLAG	20-50	25-55	5.0-20	0.5-30	1.0-4.0	1.0-15
BLAST FURNACE SLAG	36-50	30-42	7.0-18	2.0-12	0.4-1.1	0.4-1.1

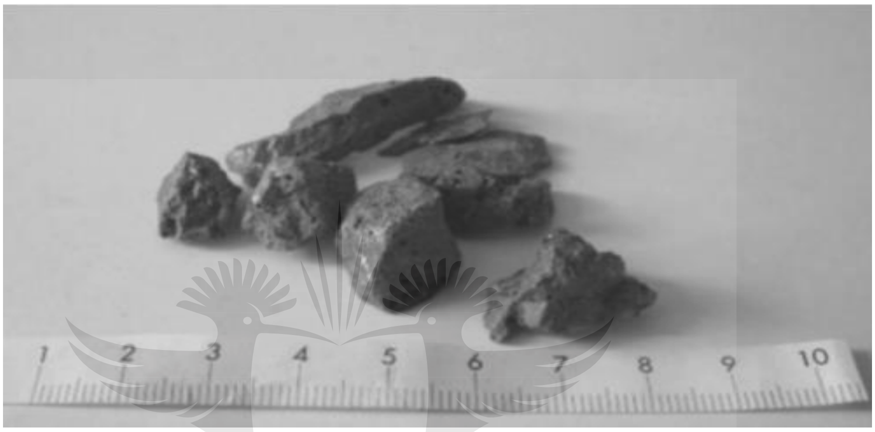


Figure 4.4: The general appearance of cupola furnace slag (Baricov et al., 2010)

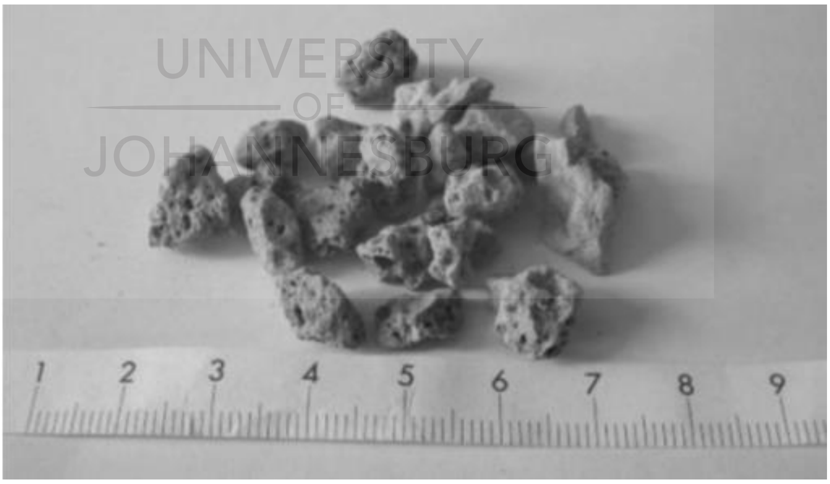


Figure 4.5: The general appearance of blast furnace slag (Baricov et al., 2010)

The chemical properties and characteristics of cupola furnace slag for the most part depend on the properties of raw materials that are utilized, specific procedures, temperature, time of thermal treatment, and the like. Subsequently, the use, treatment and discarding techniques similarly rely on these properties (Ladomersk et al., 2016). One very crucial chemical property of slag is its acidity/alkalinity. Blast furnace slag is acidic fluctuating between the range 1 – 1.1. Cupola furnace slags range from acidic to alikali. From mineralogical angle, blast furnace slag comprises gehlenite and akermanite ($2CaO.Al_2O_3.SiO_2$ - $2CaO.MgO.2SiO_2$); also monticellite ($CaO.MgO.SiO_2$), merwinite ($3CaO.MgO.SiO_2$), rankinite ($3CaO.2SiO_2$), dicalcium silicate ($2CaO.SiO_2$), pseudowollastonite ($CaO.SiO_2$) and silicate glass (which may also be included). The structure of cupola furnace slag is made mostly by silicates with respect to acidic slag. The common minerals are wollastonite ($CaO.SiO_2$), fayalite ($2FeO.SiO_2$) and other structural constituents, particularly mixtures of SiO_2 – Al_2O3 – CaO. Research has shown that the chemical composition of cupola furnace slag is almost identical to gehlenite (Uehara and Sakurai, 1996). This emphasizes the similarities between blast furnace and cupola furnace slags.

Lastly, physical characteristics of these slags are mostly due to the manner in which the molten slag is cooled and allowed to set. Depending on the way the slag is cooled, decreased or increased, crystallization of specific structural constituents happens. The subsequent proportion of crystalline and glassy phases is what influences the ability of slags to be ground. Their mineralogical structure and size of crystal stones impacts their strength and resistance to abrasion. The blast furnace and cupola furnace slags are not utilised in metallurgic production so it becomes necessary to modify them, if need be, in order for them to be utilized outside the metallurgic processing (Baricov et al., 2010).

4.2.4 Use of Cupola Furnace Slag in Concrete Making

In numerous foundries in different countries, the expenses of disposing off cupola furnace slag are trivial; nevertheless the need for its use is expanding (Ladomersk et al., 2016). This underscores the necessity to determine ways in which cupola furnace slag can be utilised. Since the chemical composition of cupola and blast furnace slags is similar to some extent, research was carried out to see if cupola furnace slag can also be utilised in concrete making.

4.2.4.1 Aggregate mix of cupola furnace slag and blast furnace slag

Experiments were carried out by Baricova and others to determine if cupola furnace slag can be used in concrete mixtures (Baricova et al., 2010). Initially, cupola furnace slag replaced 100% of blast furnace slag in concrete mixtures and these proved not feasible because the resulting strength properties were not adequate. Table 4.3 shows that cupola furnace slag generally has much higher MgO content than blast furnace slag. Large amounts of MgO reduce the quality of concrete. Whenever MgO is hydrated forming $Mg(OH)_2$, which has a volume larger than the total of the volumes of MgO and H_2O on their own, the autogenous expansion is increased. In some cases, $Mg(OH)_2$ may even double the sum of the volumes of MgO and water. Large amounts of such MgO create undue expansion as hydration is starting. This will cause unwanted expansion in the concrete and hence causing the concrete to disintegrate (Du, 2005) and (Cody et al., 1994). Therefore, mixtures with ratios of 90:10, 80:20 and 70:30 of blast furnace slag and cupola furnace slag were used in the next experiments. The samples were hardened in water for 28 days. The resulting compression strength and tensile bending after 28 days is as shown in Table 4.4:

Table 4.4: Resulting compression strength and tensile bending after 28 days (Baricova et al., 2010)

	Compression strength [MPa]	Tensile Strength [MPa]
A (100% CUPOLA FURNACE SLAG)	3.2	1.0
B (10% CUPOLA FURNACE SLAG)	10.0	3.3
C (20% CUPOLA FURNACE SLAG)	12.0	4.3
D (30% CUPOLA FURNACE SLAG)	13.0	3.8
STN 73 6123 (road concrete)	28.0	4.0
STN ENV 206-C 8/10 (plain concrete)	8.0	-
STN ENV 206-C 12/15 (plain concrete)	12.0	-

These results in Table 4.4 show that concrete mixtures using both blast-furnace and cupola slags do not comply with standards for road concretes (STN 73 6123). Nevertheless, mixtures B, C and D comply with standards for plain or ordinary concretes with lower strength properties (STN ENV 206 –C 8/10 and STN ENV 206 – C 12/15) (Baricova et al., 2010).

4.2.4.2 Cupola Furnace Slag Partially Replacing Ordinary Portland Cement

A study by Alabi and Afolayan, (2013) determined the likelihood of utilizing cupola furnace slag as part substitution of cement and as aggregate in concrete. The sand and cupola furnace slag were utilized as aggregates. It was concluded that the consistency of the concrete was adequate. Compressive strength was acceptable in comparison with usual aggregate concretes. This demonstrates that concrete with a partial replacement of the Portland cement with small amounts of granulated cupola furnace slag will give good quality concrete.

4.2.4.3 One-Year Properties of Concrete With Partial Substitution of Natural Aggregate by Cupola Furnace Slag

An experiment was carried out to test concrete with partial substitution of aggregate by cupola furnace slag in comparison with normal concrete (Ladomersk et al., 2016). The results showed that 25.5% substitution of 0.4 mm fine natural aggregate by 0.4 mm cupola furnace slag in concrete gives similar results to those of normal concrete:

1. This replacement gave a consistent and compact microstructure, a clear improvement in hydration and fine pore structure.
2. The created microstructure with cupola furnace slag was suitable for providing adequate mechanical properties to the concrete.
3. After one year, concrete with cupola furnace slag replacements demonstrated that it upholds its properties (Ladomersk et al., 2016).

From these results it is clear that conditional utilisation of cupola furnace slag in concrete making is feasible. However, the concretes will not be appropriate for busy road concretes, but they are acceptable for plain concretes that are mainly utilized for foundations of buildings, principal parts of framed structures and similar structures (Baricov et al., 2010). Having observed that the cupola furnace slag is only used in minute quantities in concrete making, it was necessary to look further at other possibilities of utilising this slag.

4.2.5 Other Possible Uses of Cupola Furnace Slag

4.2.5.1 Application of foundry slag for metal cutting - performance as a diffusion inhibitor

Research was carried out on the possible uses of cupola furnace slag in metal cutting (Uehara and Sakurai, 1996). A particular oxide contained in the matrix of calcium deoxidized steel was described to intensify the machinability of the steel in high speed cutting when a carbide cutting tool was utilized. The oxide film fastened itself on the rake face of the cutting tool and its main constituent is gehlenite. The gehlenite ($2CaO\text{-}A1_20_3\text{-}Si0_2$) is an indistinct material that generally has a low melting temperature of about 15OO^oC. It has a tendency to be collected and diffuse over the tool-chip interface in metal cutting under a definite set of cutting conditions. Research has demonstrated that the gehlenite or comparable compounds act as heat diffusion inhibitor at the tool-chip interface in machining steel. Bouhifd et al., (2002) reported that gehlenite can be manufactured from three components: Al_2O_3, SiO_2 and CaO. It was similarly predicted that the slag collected from cupola furnaces is generally the same as the gehlenite. The nature of the slag exhausted from cupola was analysed and the possibility to use it for steel cutting was examined. The conclusions were as follows (Uehara and Sakurai, 1996):

i. The chemical composition of the slag is close to being identical to the gehlenite and its characteristics resemble those of the gehlenite in metal cutting.
ii. Adding slag powder in intervals during steel cutting reduces the crater wear when a type K carbide tool is used. (Carbide tools optimised to cut grey malleable cast irons).
iii. The use of slag powder as a solid lubricant in cutting reduces flank wear.
iv. The slag can be utilised as an alternative for gehlenite. Especially, the utilisation of the slag in interval high speed steel cutting with type K carbide tool will have a useful significance.

4.2.5.2 Use of cupola furnace slag in the manufacture of ZSM-5 and NA-A zeolites

Zeolite in its natural state is a good water filter. It performs better than sand and carbon filters, resulting in cleaner water and higher output rates with less maintenance requirements. It can be utilised without any modifications.

An examination was done on creation of Na-A sort zeolites from two industrial wastes (Anuwattana and Khummongkol, 2009). The outcome demonstrated that fused sodium aluminosilicate may be effectively changed into Na-A zeolite. The ideal precursor is the mixing with treated cupola furnace slag.

In another research ZSM-5 type zeolites were prepared from cupola slag waste using both conventional hydrothermal and microwave syntheses at 130–200^{o}C (Anuwattana and Khummongkol, 2009). The possible quantity of cupola slag which can be used in the commercial manufacture of ZSM-5 by both the conventional and the microwave treatments is critical from the perspective of its reuse and of environmental impact.

4.3 Selection of The Most Probable Use of Cupola Furnace Slag

The use of cupola furnace slag in concrete making has the main disadvantage of only being successful when used in very small quantities. Hence, from all these possible uses of cupola furnace slag both companies and the researcher were interested in its use in metal cutting. What mostly attracted both companies to that possibility is the fact that cupola furnace slag is used as received or with minimal modification.

- Craster International, in Harare, is composed of two main sections: the foundry and the machine shop. So, this possibility brought to them immediate use that rids them of the industrial waste and bring savings to them by extending the life of their tools without the use or purchase of soluble oil as lubricant.
- For Midlands Metals, in Gweru, the composition of their slag and that of gehlenite are even more closely related, so this possibility is the closest to reality for them. Further looking into possible commercialisation of what has been waste for them made this possibility very exciting.
- For the researcher, waste utilisation became the immediate attraction. Management of waste falls under environmental sustainability. Minimising waste is one of the most productive ways to attaining greener manufacturing. Many other challenges are considered as waste in these fabrication businesses too. For example, lack of efficiency in energy and water utilisation, toxic gaseous emissions and the carbon footprint. All these negatively impact environmental sustainability significantly (Latif et al., 2017).

With all this in mind, experiments were set up to see the effect of the two samples on cutting of steel.

4.4 Hypothesis formulation

A hypothesis was developed that cupola furnace slag could have properties, elements and oxide compositions closer to those of Gehlenite and hence has the potential to be reused as a dry lubricant in the machining of steel.

4.5 Comparison of Gehlenite to the Cupola Furnace Slag Samples

Gehlenite is a mineral of the melilite group. It is an amorphous material that is generally transparent to translucent. Its chemical composition comprises Aluminium, Calcium, Silicon and Oxygen. The chemical formula is $Ca_2Al(AlSi)O_7$ and the molecular weight = 274.20u. Figure 4.6 shows a yellowish-brown anhedral gehlenite associated with black magnetite and white wollastonite. Gehlenite can be made artificially from three elements: Al_2O_3, SiO_2 and CaO (Bouhifd et al., 2002). The percentage chemical composition as elements and as oxides is as shown in Table 4.5:

Table 4.5: Element and Oxide composition of Gehlenite as a percentage (Mineralienatlas, 2017)

Element	Composition (%)	Oxide	Composition (%)
Calcium	29.24	CaO	40.90
Aluminium	19.68	Al_2O_3	37.20
Silicon	10.24	SiO2	21.90
Oxygen	40.84		
Total	**100.00**	**Total**	**100.00**

In order to determine the chemical compositions of the two samples of cupola furnace slags, Peacocke & Simpson laboratory used the test X-ray fluorescence test. This test is the emission of distinctive (or fluorescent) X-rays from a material that has been excited by bombarding with high-energy X-rays or gamma rays. The results are shown in Table 4.6.

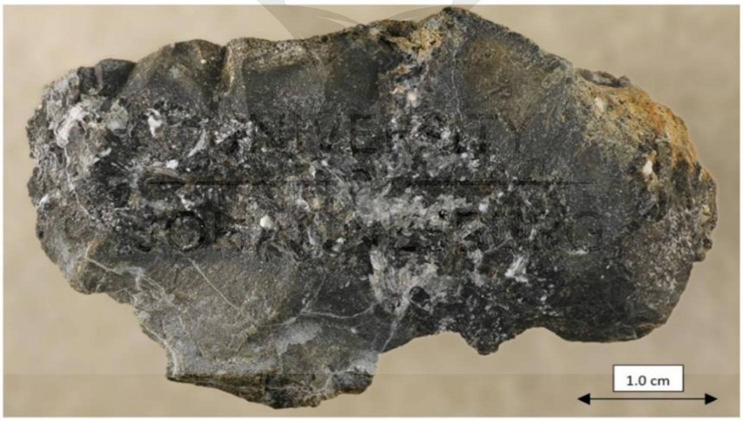


Figure 4.6: Gehlenite (Mineralienatlas, 2017)

Of greatest interest in both samples is the presence of the three elements Silicon, Aluminium and Calcium. These are the three elements that can be used to produce Gehlenite artificially. In the Craster International sample, the highest element percentage are Silicon, Calcium, Magnesium and Aluminium. The Midlands Metals sample has the highest percentage of elements in Silicon, Aluminium and Calcium as shown in Table 4.6. This indicates that these samples are chemically related to Gehlenite.

Table 4.6: Sample compositions

	Craster International Sample	Midlands Metal Sample
Element	**Percentage (%)**	**Percentage (%)**
Chromium (Cr)	0.537	1.375
(Iron) Fe	2.423	5.257
Aluminium (Al)	8.044	13.187
Magnesium (Mg)	9.200	4.602
Silicon (Si)	15.309	19.378
Calcium (Ca)	14.273	6.747
Manganese (Mn)	1.255	5.803
Nickel (Ni)	0.003	0.014
Balance Composition is Oxygen		

In the experiments of Uehara and Sakurai, (1996) Gehlenite and similar compounds were observed to attach themselves to the rake face of the cutting tool thereby acting as a heat diffusion inhibitor at the tool-chip interface. From the chemical compositions shown in Table 4.6, the two cupola furnace slag samples are similar to Gehlenite and their colours, as can be seen in Figure 4.3, suggest the presence of Carbon. Carbon is known to reduce coefficient of friction. These factors then led to experiments being carried out to determine if any of the two cupola furnace slag samples or both may be used as solid lubricants (through heat inhibition and reduction of friction) in the cutting of steel.

4.6 Experiments to Determine the Ability of Cupola Furnace Slags to Act as Lubricants in Steel Cutting

Two identical sets of five experiments were carried out in the machine shop at Craster International. In all the experiments the only variable was the lubricant. Each lubricant was used twice, once in each set. The tool readings were done before and after the experiments in the workshops at Harare Institute of Technology, in Harare, with the permission from the Ministry of Small to Medium Enterprises.

4.6.1 Materials and Methods

Materials used in the experiments are explained in this section. 19%Si,7%Ca,13%Al slag powder, 15%Si,14%Ca,8%Al slag powder, soluble oil, slag pastes made by mixing the powders with Vaseline were used as lubricants. Soluble oil that is used at Craster International is called Almaredge BI and is supplied by Castrol. It was used to serve as the control experiment. The slag rocks were ground into fine powders as shown in Figure 4.7.

(a) (b)

Figure 4.7: Slag samples ground into powder (a) 15%Si,14%Ca,8%Al slag (b) 19%Si,7%Ca,13%Al slag

A steel sieve, shown in Figure 4.8, was used to specify the particle size of the powders. It is a mesh size 16 using the Tyler Mesh Size system, meaning that it has 1mm openings. This was used in order to identify the size of particles used. This opened opportunities for growing the experiment by using different sizes of powder particles.

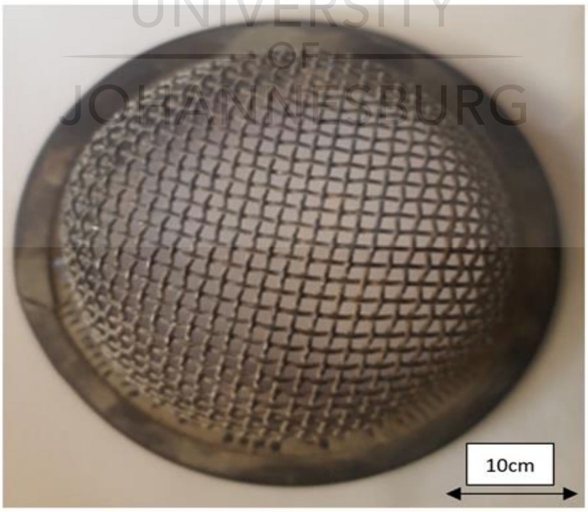


Figure 4.8: the #16 mesh size sieve that was used

Starch paste or Vaseline were suggested, in the experiments by Uehara and Sakurai (1996), to be used in some of the experiments. Either of the two may be mixed with the slag powders forming slag pastes. Vaseline was used in these experiments and the lubrication abilities of pastes and powders compared. Having lubrication abilities that are comparable would then have the paste used in some processes where it is inconvenient to use powder lubricants. In both cases 150ml of Vaseline was mixed with 75 g of each slag powder. Figure 4.9 shows the amount of 19%Si,7%Ca,13%Al slag powder used being weighed. The consistency and the workability of the paste is what determined the quantities used. The active ingredient should still have been the slag but in a form of a paste then, meaning that the powder needed to dominate the paste. Figure 4.10 shows the appearances of the pastes.

Figure 4.9: (a) Initial reading before the slag is added (b) weight of the slag shown

Figure 4.10: (a) 19%Si,7%Ca,13%Al paste (b) 15%Si,14%Ca,8%Al paste

Five identical drill bits (DO0630 A100 Dormer Jobber Drill) were used, one used twice in the experiments. They were supplied by Mining & Industrial Suppliers (PVT) LTD. Figure 4.11 (a) shows the drill bits before use, (b) and (c) are showing one of the drill bits having its full length measured. They are made of High Speed Steel material and do not have any form of coating that might assist with lubrication as is the norm in other types of drill bits. Each has the full length of 152.2mm, flute length of 100mm, diameter of 13mm, point angle of 118°, and a helix angle of 30°.

Figure 4.11 (a): 13mm high speed steel drill bits

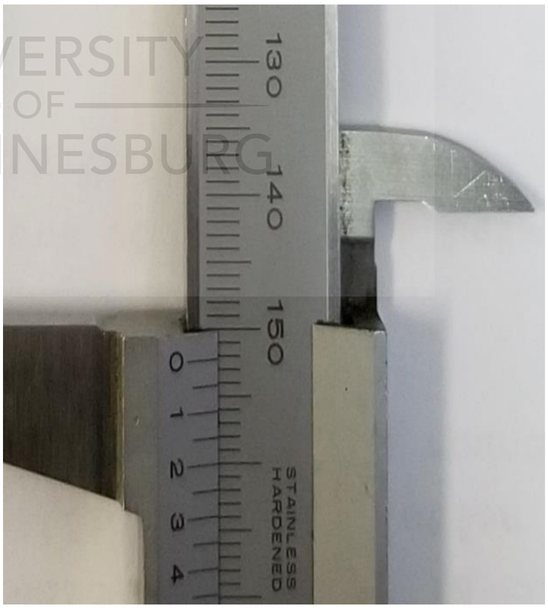


Figure 4.11 (b): full length of the drill bit **Figure 4.11 (c): full length of 152.2mm**

Holes were drilled into a 30mm thick boiler plate steel (BS 1501-151 Grade A) bar shown in Figure 4.12. The length and width of the component was 2000mm by 300 mm.

Figure 4.12: The steel bar mounted on the drilling machine

The machine used is a Radial Drilling Machine called Drummond – Asquith, Machine No. P24029.

(a) **(b)** **(c)**

Figure 4.13: Drilling processes (a) using the soluble oil (b) using slags in powder form (c) using slag pastes

Figure 4.13 shows how the experiments were carried out. Each drill bit drilled a total of 40 holes with drill bit diameter readings being taken after the first set of 20 holes each and after the total 40 holes. The spindle speed used for all the experiments was 250 rev/min and a feed rate of 0.21 mm/rev. The control experiments were carried out using soluble oil as the lubricant. The drilling was continuous and the liquid was continuously poured into each hole as it was being drilled down. The drilling was also continuous when using powder lubricants with the powder continuously being pushed down into each hole as it was being drilled down. The other two sets of experiments utilised the 19%Si,7%Ca,13%Al paste and 15%Si,14%Ca,8%Al paste. At the start of the first hole the paste was applied on the drill bit, as the drilling continued the drill bit was periodically pulled out and the paste pushed into the hole and drilling continued until the hole was fully drilled. The nature of the paste required that peck drilling be the type of drilling of choice. The drill bits were each labelled after its first 20 holes as shown in Figure 4.14.

Figure 4.14: Labelled drill bits

In addition to checking the diameters after the experiments, it was crucial too to check if there were any cracks on the drill bits. An Optical Profile Projector shown in Figure 4.15 was used to check for any cracks on the drill bits. The magnification of the drill bits made it easier to check for cracks.

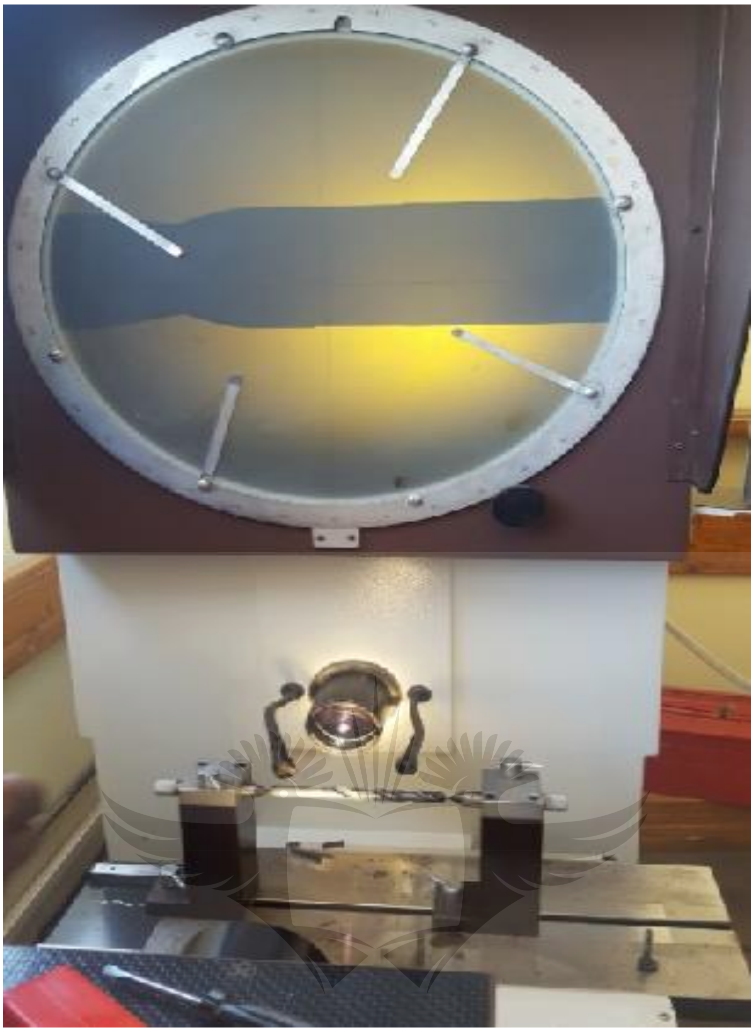


Figure 4.15: The Optical Profile Projector used in checking for cracks.

4.6.2 Results and Discussion

A. Results

All the holes that were drilled are shown in Figure 4.16. (a), Figure 4.16(b) shows the entry side and Figure 4.16 (c) shows the exit side.

Figure 4.16 (a): All the 200 holes that were drilled in all the experiments

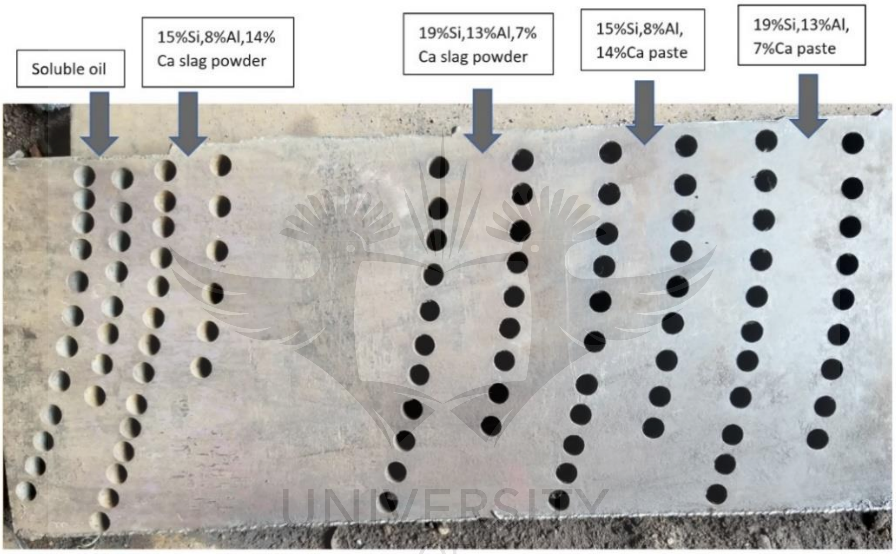


Figure 4.16 (b): Holes drilled – the entry side

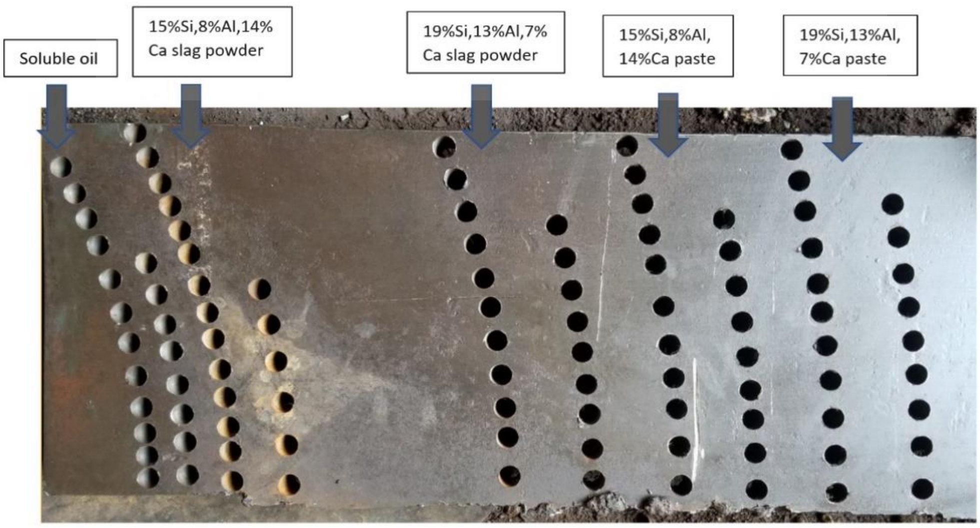


Figure 4.16 (c): Holes drilled – the exit side

As can be seen in Figure 4.16(c) the drilling process produced minimal to no burr at all. Entry and exit diameters of three random holes per lubricant were measured using a T-gauge as shown in Figures 4.17 (a) and (b). All the measured holes had diameters of 13mm projecting that all the holes have a diameter of 13mm, showing that the process was carried out correctly. Figure 4.17 (c) and (d) show that the measured holes are 13mm in diameter.

(a)

(b)

(c)

(d)

Figure 4.17: A T-gauge was used to check the diameter of holes confirming diameters of 13mm each

Drill bits diameter readings before and after the experiments are shown in Tables 4.7 (a) – (d).

Table 4.7 (a): Drill bit diameter readings before the experiments

Drill bit	First reading (mm)	Second reading (mm)	Third reading (mm)
1	13.000	13.000	13.000
2	13.000	13.000	13.000
3	13.000	13.000	13.000
4	13.000	13.000	13.000
5	13.000	13.000	13.000

Now with labelled drill bits:

Table 4.7 (b): Drill bit diameter readings after the first 20 holes on each drill bit

Corresponding lubricant used on the drill bit	First reading (mm)		Second reading (mm)		Third reading (mm)	
	After 20 holes	After 40 holes	After 20 holes	After 40 holes	After 20 holes	After 40 holes
Soluble oil	12.990	12.980	12.990	12.980	12.990	12.980
19%Si,13%Al,7%Ca Powder	13.000	12.990	13.000	12.990	13.000	12.990
19%Si,13%Al,7%Ca Paste	12.990	12.990	12.990	12.990	12.990	12.990
15%Si,14%Ca,8%Al Powder	12.980	12.930	12.980	12.930	12.980	12.930
15%Si,14%Ca,8%Al Paste	12.985	12.930	12.985	12.930	12.985	12.930

Table 4.7 (c): Entry and exit diameter readings on three random holes per lubricant after 40 holes

Corresponding lubricant used on the holes	First reading (mm)		Second reading (mm)		Third reading (mm)	
	Entry	Exit	Entry	Exit	Entry	Exit
Soluble oil	13.000	13.000	13.000	13.000	13.000	13.000
19%Si,13%Al,7%Ca Powder	13.000	13.000	13.000	13.000	13.000	13.000
19%Si,13%Al,7%Ca Paste	13.000	13.000	13.000	13.000	13.000	13.000
15%Si,14%Ca,8%Al Powder	13.000	13.000	13.000	13.000	13.000	13.000
15%Si,14%Ca,8%Al Paste	13.000	13.000	13.000	13.000	13.000	13.000

Table 4.7 (d): Drill bit average diameter measurements and corresponding average hole diameters

Lubricant used	Average initial drill bit measurement (mm)	Average final drill bit measurement (mm)		Corresponding holes average diameter (mm)
		After 20 holes	After 40 holes	
Soluble oil	13.000	12.990	12.980	13.000
19%Si,13%Al,7%Ca Powder	13.000	13.000	12.990	13.000
19%Si,13%Al,7%Ca Paste	13.000	12.990	12.990	13.000
15%Si,14%Ca,8%Al Powder	13.000	12.980	12.930	13.000
15%Si,14%Ca,8%Al Paste	13.000	12.985	12.930	13.000

These changes are clearly shown in Figure 4.18:

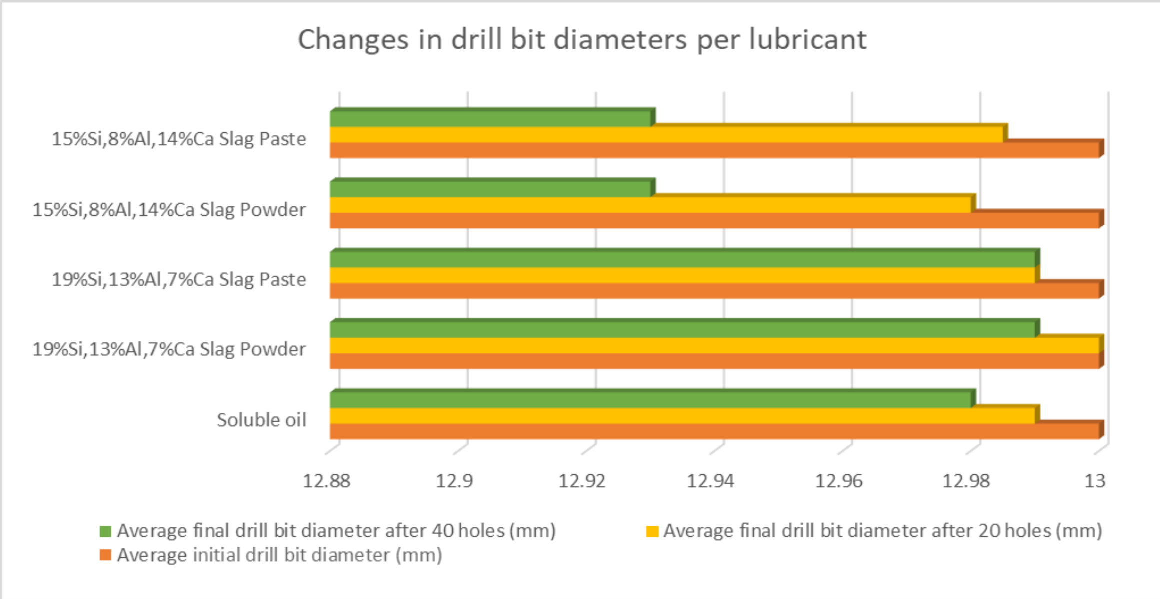


Figure 4.18: Changes in drill bit diameter

The slag that had 13% Al outperformed the slag that had 8% Al in both states as a powder and as a paste. Since these elements exist as oxides in the slag it means that the better performing slag has higher quantities of Al_2O_3 in it. This tallies well with the use of Al_2O_3 in tool coatings. The coating used on tools is a layer that is about few micrometres thick consisting of hard, anti-friction, chemically inert and thermal isolating materials. Therefore, coated tools perform better under mechanical and thermal loads, reduce friction and improve resistance to wear in a wider range of cutting temperature when compared to the tools that are not coated (Bouzakis et al., 2012). Al_2O_3 has exceptional chemical stability and in coating brings in high temperature resistance, high hot hardness and wear resistance. In temperatures higher than 800°C, Al_2O_3 in coating gives the best hot hardness. Its resistance to oxidation is high due to its chemical inertness together with electrical insulation (Bobzin, 2017). A higher Al_2O_3 content at the tool-workpiece material interface improves tooling performance.

After the drilling of 40 holes, each drill bit experienced some level of flank wear, some more than others. Figure 4.19 shows labelled drill bits at close range compared to a brand-new drill bit. In figure 4.19 all the drill bits show minimal flank wear with the drill bit that used Midlands Metals powder as its lubricant being the least affected. The ones that used Soluble oil and 19%Si,13%Al,7%Ca pastes are comparable and are the next to be least affected. The two that used 15%Si,8%Al,14%Ca powder and paste were the worst affected.

Figure 4.19: Used drill bits at close range being compared to a brand new one

Figure 4.20 shows the used drill bits from a top angle view again being compared to a brand-new drill bit.

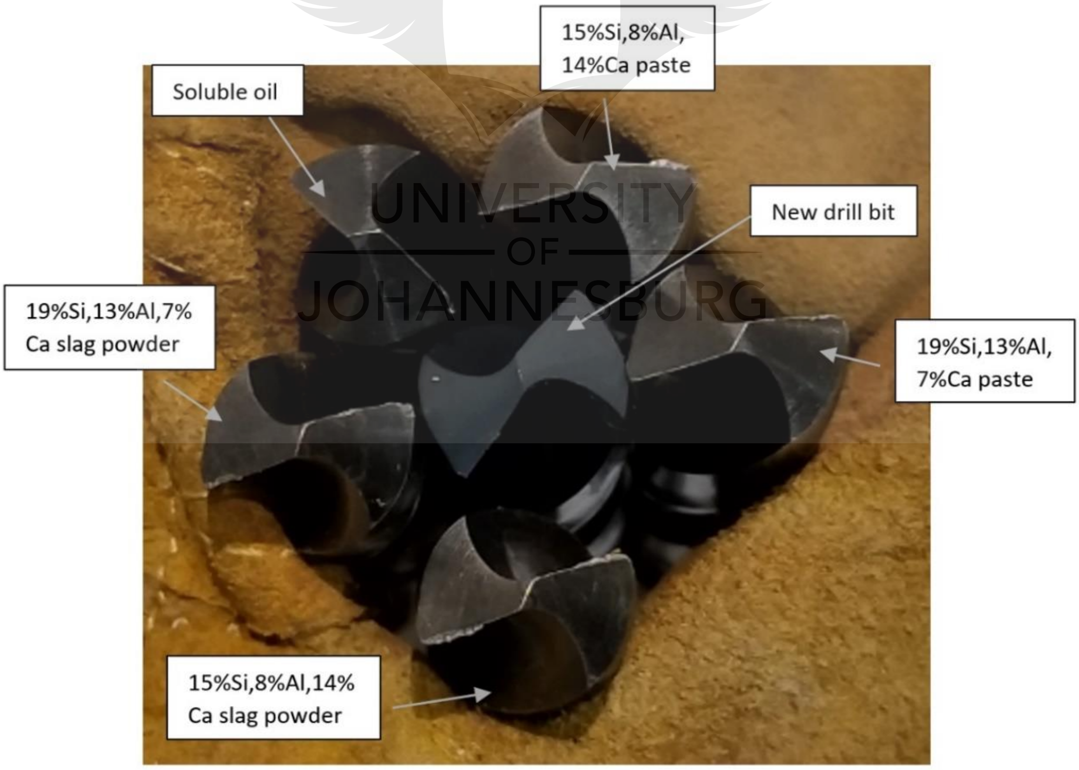


Figure 4.20: Top angle view of the used drill plus the brand new one

Flank wear is clearer from the top angle view. All the drill bits have worn out visibly.

B. Discussion of Results

The results above can be explained as follows:

1. From the Optical Profile Projector as can be seen in Figure 4.15 all the drill bits were not fractured during the drilling processes.
2. All the holes drilled were 13mm in diameter. This shows that the drilling processes were carried out accurately.
3. The change in diameters of drill bits after 20 holes each prove that generally the powders and pastes perform well as lubricants since the differences in the final drill bit measurements are all comparable to the final measurement of the control drill bit. However, after 40 holes each, the performance of the 15%Si,14%Ca,8%Al slag, both as a powder and as a paste, drops considerably as the two drill bit diameters decrease by a much larger margin.
4. The addition of Vaseline reduced the lubrication properties of the 19%Si,7%Ca,13%Al powder slag, while it improved the properties of 15%Si,14%Ca,8%Al powder slag after 20 holes per drill bit and showed an effect on the latter set of 20 holes per drill bit. This implies that addition of Vaseline has little consequences on the properties of the slag powders. In cases where it is impossible to use a powder lubricant, then Vaseline may be added to produce pastes.

4.7 Conclusion and Recommendations

4.7.1 Conclusions

The aim of this research is to identify ways in which two foundry companies in Zimbabwe can utilise the cupola furnace slag that is currently produced as waste. This research showed that cupola furnace slag may be used in:

i. concrete making as partial replacement of blast furnace slag as aggregate and as partial replacement of Portland cement
ii. production of Na-A and ZSM-5 types Zeolites

A further experiment into the research then showed that the 19%Si,7%Ca,13%Al slag may be used as a lubricant in steel cutting. It acts as a diffusion inhibitor thereby giving potential for elongating the tool life. Looking at Table 4.6, the 19%Si,7%Ca,13%Al slag had calcium, aluminium and silicon as the elements with the highest content. This makes its properties closer to those of Gehlenite than to the 15%Si,14%Ca,8%Al slag properties. This explains the better performance of slag that has a high aluminium and silicon content as a lubricant in steel cutting. Gehlenite had already shown that it can be used as a lubricant in steel cutting in earlier research. The selection of that slag with a high aluminium and silicon content will help in its use as solid lubricant in dry drilling. Promoting dry drilling will also advance sustainability by reducing on the use of oil-based cutting fluids thus cutting costs and eliminating the environmental burden of oil usage. It is also noted that both elements are key constituents of coatings for cutting tools.

4.7.2 Recommendations

The use of cupola furnace slag in steel cutting is the easiest of the three suggestions that came out of this work. This is because the slag can be used as a powder lubricant directly from their landfills. The only process that is required is grinding it to a powder form. For future work, it is important to investigate the use of cupola furnace further by:

1. carrying out more drilling trials and test the repeatability of the results and application to other materials and cutting processes. This will also help to explain the drop in performance of the 15%Si,14%Ca,8%Al slag in the second set of 20 holes per drill bit.
2. grinding the powders to different sizes to see if this changes the result, and if it does, evaluate the optimum size of powders for improved machining performance.
3. using another waste stream material as an alternative to Vaseline.
4. checking the composition of the fumes that are produced while using pastes to find out if they affect the operator.
5. carry out the experiments on harder materials such as titanium comparing the lubrication and heat diffusion properties of cupola furnace slag to those of lubricants used in these heavier cuts.

These recommendations will help the environment by utilising cupola furnace slag which is currently just being disposed of as a waste in landfills. The companies will benefit by not spending any more on buying soluble oils as lubricants.

Chapter 5

CALCINATION OF LIMESTONE – A SMALL COMPANY IN ZIMBABWE

5. 1 INTRODUCTION

5.1.1 Background – JMK Trading Company

In Zimbabwe many companies are slowing down, even shutting down, due to a number of challenges and mainly the economic challenges facing the country. However, a new company, JMK Trading, started up in Gweru in the year 2016. The main line of production is the preproduction of limestone. The company employs 20 people at full capacity and all reporting to one manager and owner of the company. The main challenge at JMK Trading is the emissions of greenhouse gases. There are two three-tonne kilns, shown in Figure 5.1. As seen in the picture, gases are released into the air directly. There are no measures in place yet to mitigate the greenhouse gases that are being emitted directly into the air (Mashavakure, 2017).

Figure 5.1: The two kilns at JMKT, each at 3000kg capacity

Figures 5.2a - d show the construction process for the kilns. Figure 5.2b shows the draw hole that allows the air for combustion through and from where the quicklime is collected. On top of the draw hole are the kilns that are built with two walls.

(a)

(b)

(c)

(d)

Figure 5.2: Construction phases of the kilns

The inner wall is made from refractory bricks and the outer wall is made of a stronger quality brick. In between the two walls is an insulation to control the amount of heat that is lost from the kilns. Figure 5.2c shows one side wall that is completed. Figure 5.2d shows the inspection holes on the side walls. These are access points that allow inspection of the process.

What has helped this company to stand out when others are barely making it is the fact that it is a small company and has far less overheads. JMKT saw an opportunity to supply lime hence, started the calcination of limestone. Their target consumers are the over 50 gold mines in the country, city council (for water purification process), sugar manufacturers and eventually for export too. Currently their main consumers are the gold miners in Shurugwi (283km from Gweru), Gwanda (297km from Gweru) and Kadoma (137km from Gweru) (Mashavakure, 2017).

There is still a lot of work that needs to be done for the company to grow and in order to meet the demand of customers i.e. so that JMKT can supply lime to all its targeted consumers. All the work is still being done manually. Figure 5.3a shows quicklime to be collected using shovels by employees and figure 5.3b shows a ladder that is used to assist with the feeding of the kiln. A network of ropes is used to pull buckets of limestone up.
After the collection of the quicklime, water is added to form hydrated lime powder. This will make the transportation of the lime easier as hydrated lime will no longer react with water in cases of accidental hydration. Figure 5.4 shows hydrated lime after reaction of quicklime with water. The water is collected from a nearby stream (Mashavakure, 2017).

(a) (b)

Figure 5.3: All the processes are still done manually at JKMT

Figure 5.4: Quicklime changes to white powder when water is added to it.

The hydrated lime is then taken to the grinder where it is ground to form powder of the hydrated lime that will be ready for collection. Figure 5.5 shows the grinding mill that is powered by an electric motor. Safety is not taken into consideration here. The belt is exposed and the whole system is not guarded for health and safety of the workers.

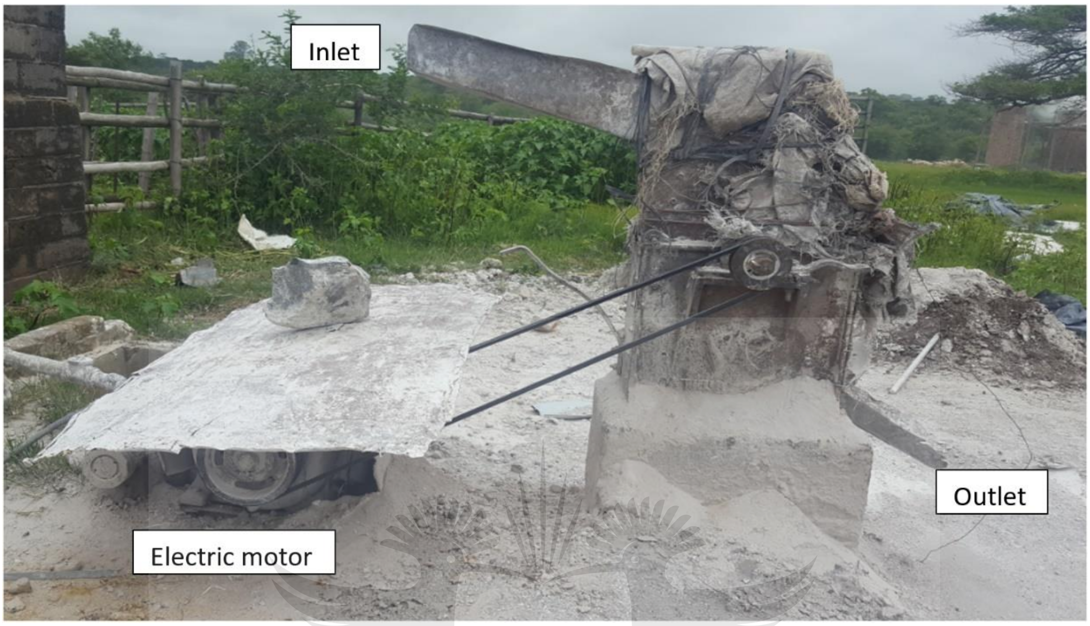


Figure 5.5: The grinding mill

Coal is used as the source of energy here. It is bought from a company in Hwange at $1300.00 per 25 tons including transportation charges. Twenty five tonnes of coal produce 100Mt of lime.

Possibilities for reducing energy cost are:

- use of insulating material such as vermiculite between the inner and outer brick skin and
- addition of a chimney to each kiln could increase draught column hence preheating of limestone

Material costs can be reduced by constructing kilns close to limestone and coal mines, but on condition there is a ready water source nearby.

5.1.2 Research Motivation

As has been delineated by all the pictures, in Figures 5.1 to 5.5, this calcination process and furnace design were achieved utilizing constrained resources. Regardless, the urgent issue that should have been attended to is the issue of greenhouse gas emissions. The point of this research was to analyse methods for making the upcoming company environmentally cordial. An intensive evaluation of the calcination plant and research brought out conceivable solutions that were then introduced to the company for implementation.

5.2 Literature Review

5.2.1 Calcination

Calcination is basically the conversion of limestone into lime. The conversion through burning brings about quicklime, calcium oxide. It may be white, amorphous and crystalline. Its specific gravity is 3.2 and melting point 2578°C (Brady et al., 2002) . Hydrated lime or Calcium Hydroxide is formed by reacting quicklime with adequate water to produce a dry white powder. Lime is utilized by an extensive range of industries for countless purposes such as:

- steel industry – where it is used as a medium for eliminating pollutions (silica, phosphorus and sulphur) in the purifying of steel. For its utilization in the steel industry, it must meet the correct physical and synthetic property requirements. Without this, the specific required standard of steel fabricated is not met.
- waste water treatment – where it is utilized to treat industrial and mining waste water. It alters the pH of acidic waste by expelling phosphorus and nitrogen. It is likewise utilized to diminish and expel polluting elements (for example, lead) from drinking water, and as an exceedingly financially sound strategy to treat sewage.
- cleaning of industrial gasses before they are discharged into the air – where it is utilized to treat stack gasses from various industrial facilities to assimilate sulphur oxides and help reduce ozone depleting greenhouse gas emissions into the atmosphere
- paper, paint, ink and plastic industry - where it is utilized to create precipitated calcium carbonate which is utilized as a part of the manufacture of these items
- cement production – where it is utilized as an ore to blend with shells, and chalk or marl joined with shale, slate, dirt, silica sand, blast furnace slag, and iron ore. These components at high temperatures become a rock like substance that is ground into the fine powder that is ordinarily considered as cement (National Lime Association, 2016).

- sugar refineries – sugarcane is harvested and mixed with water to produce crude cane juice that has a low pH and contains liquefied pollutants. Hydrated lime is added to the juice to raise the pH and to react with the pollutants producing insoluble calcium amalgams that can be taken out. Remaining lime is taken out via carbonation or adding phosphoric acid. This procedure is repeated enough times until the needed pureness of the produced item is reached. This procedure is followed in the making of sugar from sugar beets however, more lime is used in beets than that in sugar cane (National Lime Association, 2016).
- gold refineries – the Cyanide procedure includes the disintegration of gold from the ground ore in a dilute cyanide (normally NaCN or KCN) mixed with lime and oxygen. Adding lime to cyanide is widespread to avoid hydrolysis and to kill any acidic constituents display in the mineral (Eugene and Mujumdar, 2009).

5.2.2 Calcination process

Calcination of limestone is an energy absorbing procedure where limestone (calcium carbonate, $CaCO_3$) is transformed by thermal decay into lime (calcium oxide) CaO and (Carbon Dioxide) CO_2. The procedure can be described in three stages (Figueroa et al., 2008):

a) heat energy transferred by calciner gasses coming from the combustion and exhaust gases to the limestone, by convection and radiation, pre-heats the limestone from the surrounding temperature to the disintegration temperature ranging from 600^{o}C to 900^{o}C (Freund, 1998) depending on the type of limestone being converted;
b) at the disintegration temperature calcination starts, causing lime to shell around the limestone centre. The pressure of CO_2 coming from the decay of limestone at the particle surface is larger than the partial pressure of CO_2 in the surrounding gas;
c) the heat goes through the permeable film by conduction raising the inside temperature, which causes calcination to progress. The discharged CO_2 diffuses through the permeable film to the surface and by convection is discharged into the calciner. Provided that the limestone temperature continues to rise and partial pressure of CO_2 is less than the decay pressure, calcination proceeds until all the limestone is changed into lime (Mikulčić et al., 2012).

This equation illustrates the calcination process:

$$CaCO_3 \rightarrow CaO + CO_2 \quad \Delta H = +182kJ\, mol - 1$$

This shows that the forward reaction is advanced by higher temperatures, since it is endothermic, that is energy absorbing. The reaction will continue if the partial pressure of CO_2 in the gas over the hard surface is below the decay pressure of the $CaCO_3$. The pressure of the $CaCO_3$ is dictated by equilibrium thermodynamic being considered (Stanmore and Gilot, 2005).

Figure 5.6 illustrates the vertical kiln, Figure 5.7 illustrates a vertical kiln with a mechanism for collecting CO_2 and Figure 5.8 is showing the rotary kiln that may all be utilized in the calcination procedure. Kilns may have steel shells layered with refracting blocks. The design of the vertical kiln in figure 2 makes it less demanding to collect the formed CO_2.

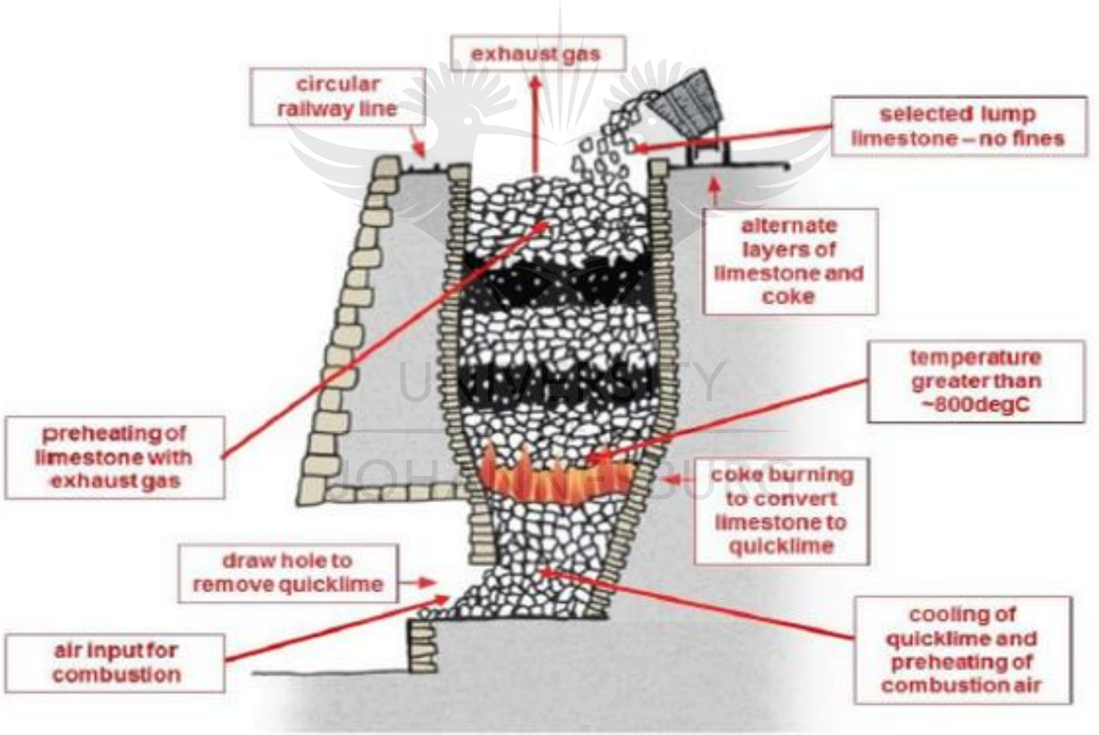


Figure 5.6: A Vertical kiln showing Calcination process (Ly, 2016)

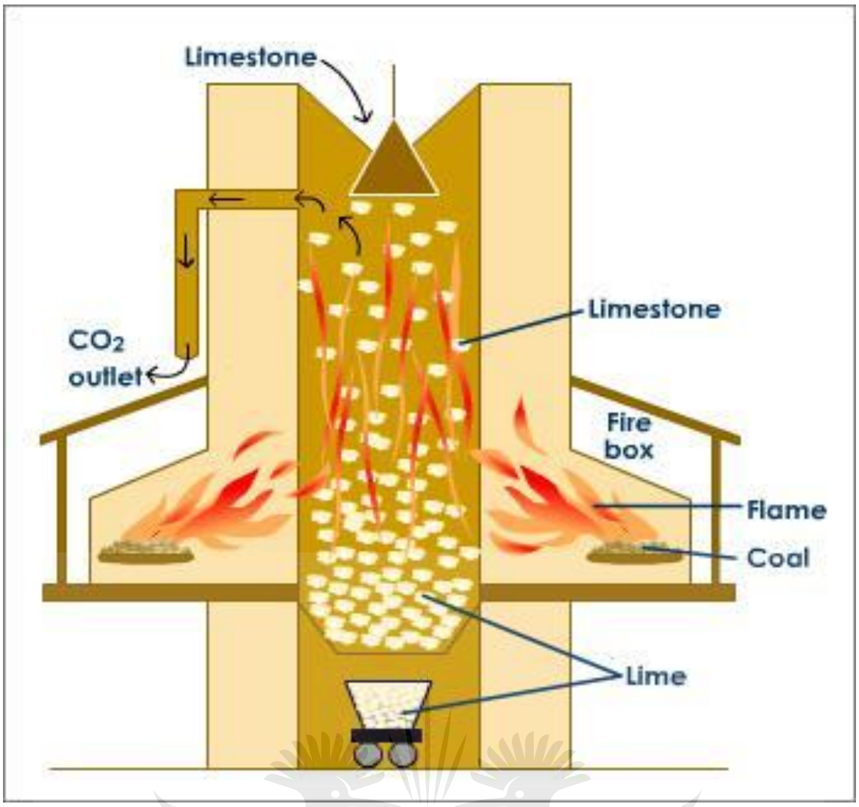


Figure 5.7: Vertical kiln with an easier mechanism for CO_2 collection (Shrestha, 2016)

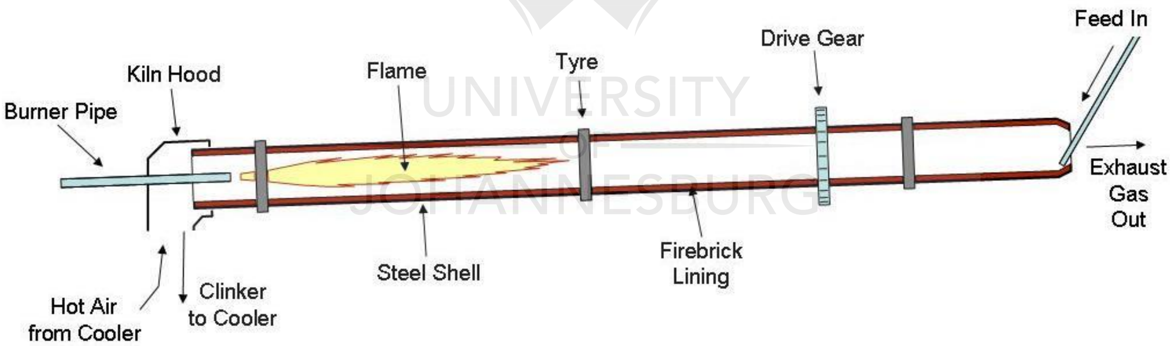


Figure 5.8: Rotary Kiln (Rafiee, 2008)

5.2.3 Furnace Construction

The primary goal of a kiln is to accomplish controlled heating at raised temperature and less fuel utilization than what could be accomplished in open air (Jenkins and Mullinger, 2011). Utilisation of a lesser amount of fuel is progressively becoming essential as fossil fuel stocks are reducing and allowable carbon discharge limits are on the rise.

Before the 19th century, kilns were constructed using block and stone. As the demand for product increased, sizes of kilns increased and the block and stone structure became vulnerable to collapse and steel supports were regularly added on the outside to reinforce the building. Over time the steel supports were made part of original designs as they were added to the elementary block structure. The rotating kiln was developed in the late 1800s and it needed that an external steel cylinder with a block lining be utilized; accordingly, another type of building was started and later it spread to other kiln types. Nowadays most heaters consist of a steel external structure and a heat resistant inside layer. Some of these constructions are illustrated in Figures 5.9, 5.10 and 5.11.

The benefits of having a steel external over fortifying a block structure with steel are:

- Reduction of gas out and air in spillages.
- Maintenance is cheaper since relining a kiln is less expensive than rebuilding it.
- In case of a blast, safety is enhanced since flying fragments are reduced
- Outline, dimensions and type of inside layer can be changed so there is more adaptability in design (Jenkins and Mullinger 2011).

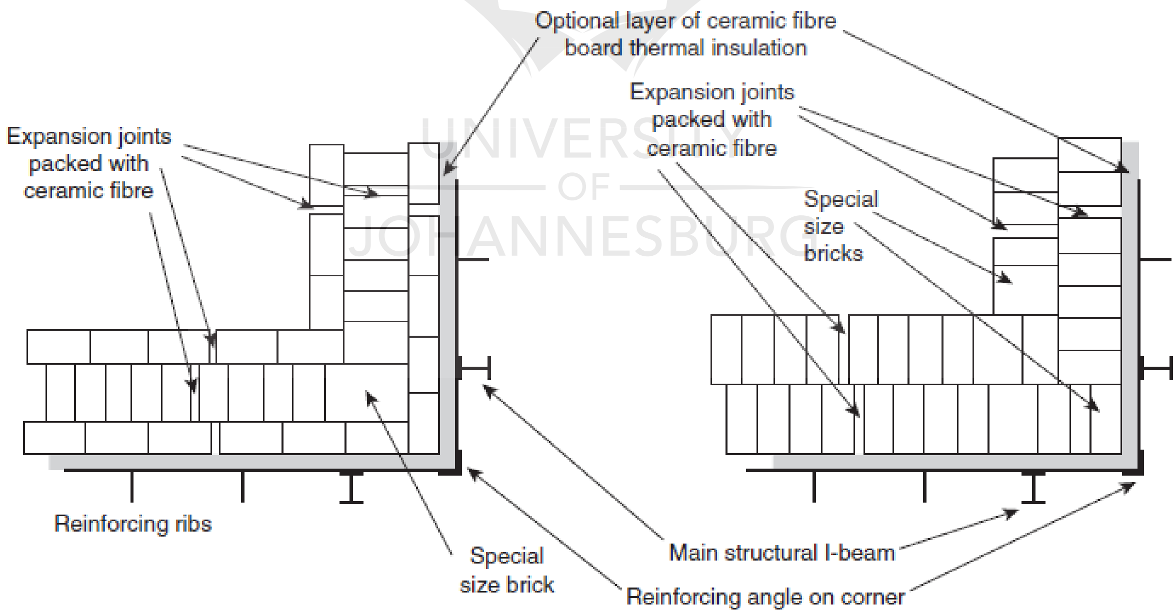


Figure 5.9: Characteristic brick lining construction showing expansion joints with steel reinforcing (Jenkins and Mullinger, 2011)

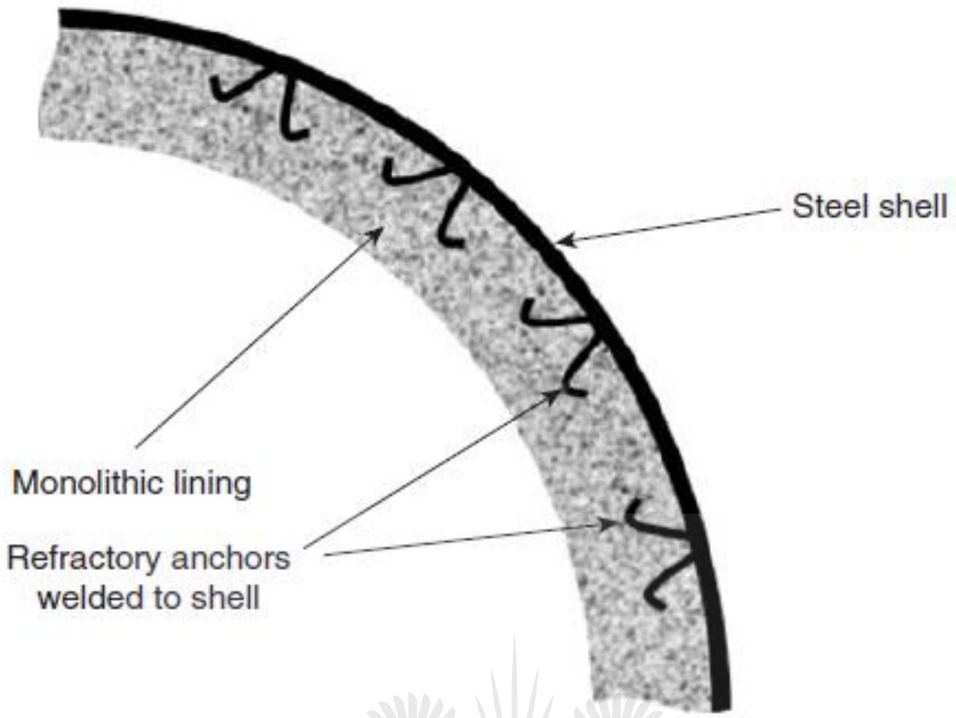


Figure 5.10: Characteristic monolithic lining held by anchors to the shell (Jenkins and Mullinger, 2011)

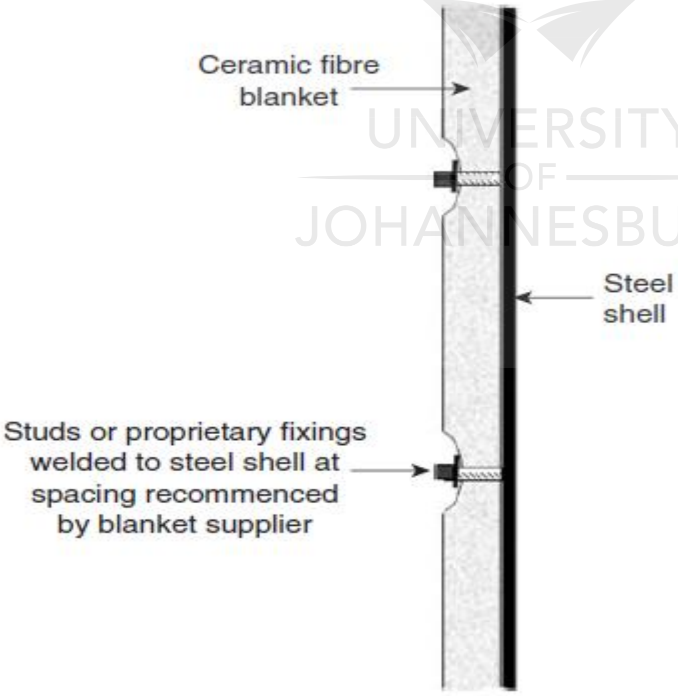


Figure 5.11: Characteristic ceramic fibre liner (Jenkins and Mullinger, 2011)

5.2.4 Basic Requirements of the Kiln Structure

A rudimentary kiln comprises a shell with a heat source. This source of heat, possibly flames of fire, supplies energy to the procedure. Using the flames, the heating might be direct or convective. Direct heating uses radiation from the fire and convective heating transmits the heat from combustion or indirectly through radiant heat from a heated wall. Figures 5.12 and 5.13 demonstrate a fundamental kiln illustrating direct fired and indirect fired heat source separately.

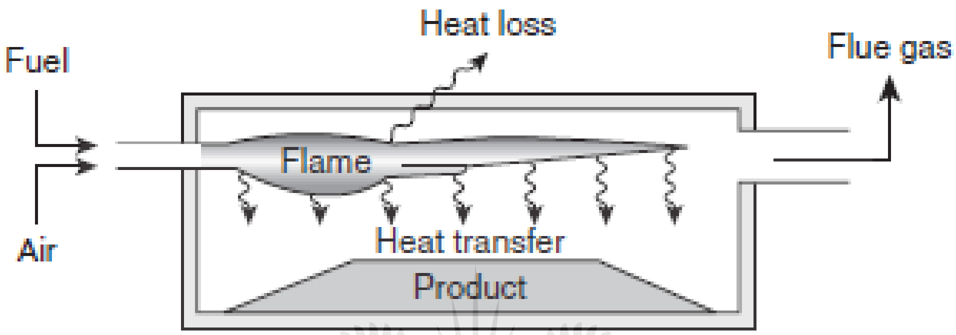


Figure 5.12: Direct heat transfer (Jenkins and Mullinger, 2011)

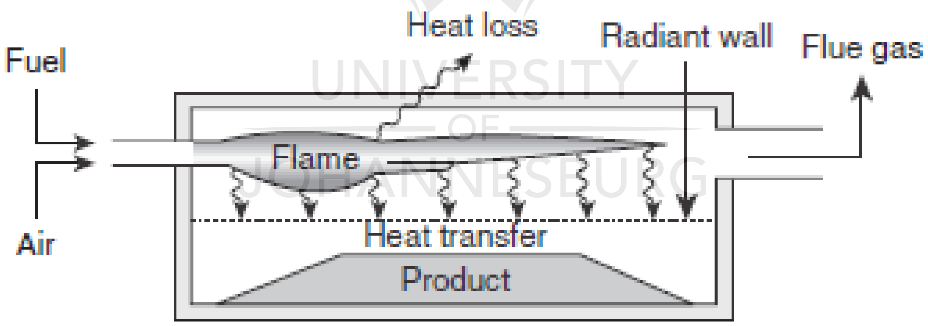


Figure 5.13: Indirect heat transfer through a heated wall (Jenkins and Mullinger, 2011)

Whatever strategy for transmitting heat that is utilized, the kiln is required to:

- have a precisely controlled environment for the procedure
- have an ideally shaped area for combustion and for viable heat transmission
- accommodate, and sometimes ferry products securely
- reduce air intake and gas spillage
- reduce radiation and convection heat losses

- have a long working life and a simple maintenance scheme.

A kiln should be designed to accommodate temperatures going from ambient up to 2000^oC in a few cases. This is a difficult task in the designing and maintenance of kilns. However, important issues that must be considered are:

- Allowance for differential thermal expansion.
- Allowance for permanent expansion caused by physical changes in the lining material during the first heating.
- Lessening of high temperature corrosion.
- Maintaining the required strength under load.
- Likelihood of a chemical reaction occurring between the product being manufactured and the kiln lining (Jenkins and Mullinger 2011) .

Resolution to these issues needs a serious focus on the individual factors such as choosing appropriate lining materials, how to accommodate the expansions and the like.

5.2.5 Effects on the Environment of the Production of CO2 during Calcination

The most recent sign of pollution is that of environmental degradation. This has been due to some level of human activity adding to the upsurge of greenhouse gasses in the atmosphere. The greenhouse gasses include Methane (CH_4) and Carbon dioxide CO_2. In order to reduce the greenhouse gasses released into the atmosphere, an extensive understanding on how to decrease CO_2 discharge from these procedures is pertinent. The calcination process has CO_2 as one of its direct products. Propositions that have been made include the capturing of CO_2 from the combustion gasses, and then discharging it in a concentrated stream in a more proficient and financially sound manner (Freund 1998). CO_2 capture and storage is slowly turning into a significant idea in diminishing greenhouse gas emissions, alongside different other alternatives, for example, the utilization of sustainable power sources, the utilization of nuclear energy and changing from coal to gas firing (Feron and Hendriks 2005). This alternative is presently better comprehended and can be compared to these older measures, for example, fuel exchanging and utilization of sustainable power source (Freund, 1998). CO_2 capture and storage will be investigated as a possible option for the Calcination Plant in the abatement of CO_2 emissions.

5.2.6 CO_2 Capture and Storage

CO_2 capture and storage is one way that will clear a path for the imaginable sustenance of the utilization of non-renewable energy sources such as coal, gas and oil, by radically lessening the CO_2 discharges. In CO_2 capture and storage, CO_2 is collected, prepared for transportation and kept in an appropriate geological sink, where it may be kept for a relatively long interval. It is then vital that CO_2 capture and storage minimises or completely stops the release of CO_2 into the air due of calcination process (Feron and Hendriks, 2005). The three stages followed in CO_2 capture and storage are:

- Capture – Huge quantities of CO_2 are discharged in dilute streams at atmospheric pressure. For CO_2 to be transported and stored, it should be concentrated. Generally, it should be close to pure CO_2 at an absolute pressure of 100 bar after capture. Accordingly, compression is done to get to the correct state for transportation and storage.
- Transportation – It is not with every case that the CO_2 storage is at the same location as the emission source. This then means that transport is required to connect the CO_2 source to the sink.
- Storage – When CO_2 is collected, it must be stored safely and blocked off the atmosphere even for long periods of time. Conceivable option is underground, e.g. depleted oil and gas fields (Feron and Hendriks, 2005).

5.2.7 CO_2 Capture Technologies

Capture and storage of CO_2 is one of the techniques used to relieve the atmosphere of greenhouse gas emissions. Every effort, no matter how small, is necessary to make sure that there are no greenhouse gasses (Feron and Hendriks, 2005). Calcination produces dilute CO_2 because of the procedure being coal/air powered. Hence, the difficult task of isolating the CO_2 from other elements in the flue gasses. It is imperative to fit in highly efficient methods that will carry out the separation at minimal costs. While assessing how best to capture CO_2, a few technologies may be tracked in order to capture CO_2 from processes that have coal as a powering source. Three of such technologies are: post-combustion capture, pre-combustion capture, and oxy-combustion (Yang et al., 2008). In post-combustion capture, the CO_2 that is isolated from other elements of the flue gas is either initially coming from the air or created in the combustion process. In pre-combustion capture, carbon is taken out of the fuel before combustion, and in oxy-ignition, the fuel is burnt in an oxygen stream that contains close to zero nitrogen (Figueroa et al., 2008). Advantages and disadvantages of the different CO_2 capture technologies are as follows:

Post-combustion - Advantages

- Applicable to most existing coal-fired plants
- Retrofit applications

Disadvantages

- CO_2 is diluted in flue gas resulting in a significant need for higher quantities of flue gasses to capture reasonable amounts of CO_2 and it is produced at lower pressure than those required for sequestration(Leung et al., 2014).

Pre-combustion - Advantages

- Synthesis gas has a high concentration of CO_2 at high pressure, bringing about need for more technologies for separation, higher driving force for separation and potential for lessening compression costs and loads

Disadvantages:

- Appropriate mostly for new plants, since few gasification plants are presently in operation
- Cost of setting up is high
- Wide supportive systems are required

Oxy-combustion - Advantages

- Flue gas has a very high concentration of CO_2
- Retrofit application

Disadvantages

- Huge cryogenic O_2 creation necessity might be unaffordable
- Chilled CO_2 reuse required to keep up temperatures inside limits of combustor materials
- Reduced process effectiveness (Figueroa et al., 2008).

The above advantages and disadvantages of different processes lead to conclusions that post-combustion capture applies primarily to coal/air-fuelled processes, pre-combustion capture is applied to gasification plants and oxy-combustion may be applied to new plants or to modify existing plants. These process classifications can be applied to both fossil biomass-based and fuel energy conversion processes i.e. power plants and industrial plants. The process specifics will however differ for each type of fuel, and each type of process. Also, for coal-based procedures the sulphur content of coal has an impact on the design, operation and costs of capturing CO_2. Power plants may be the largest point sources of CO_2 mixed in flue gases but other large single point sources of diluted CO_2 are kilns, industrial boilers, and calcining processes (Feron and Hendriks, 2005). Since the calcination process produces CO_2 as a by-product, post-combustion capture and oxy-combustion technologies can be applied to the calcining process. This is because they allow the capture of CO_2 after processing. However, one of the disadvantages of the oxy-combustion technology is that large cryogenic O_2 production requirement may be cost prohibitive and one of the challenges is that of developing a separation process that recovers CO_2 from the flue gas at acceptable costs. This then leaves post-combustion technology as the only viable technology to be used at JMKT.

5.2.8 Post-combustion CO_2 capture

This procedure removes CO_2 from the flue gas after calcination has occurred. Its capacity to be retrofitted into existing power plants makes it the ideal alternative for CO_2 capture. Nevertheless, the significant problem with post-combustion CO_2 capture is its bulky dependent load. Because the CO_2 level in combustion flue gas is usually low, related expenses for the capture unit to achieve the concentration of CO_2 (over 95.5%) that is required for transportation and storage are raised (Leung et al., 2014). The general post-combustion procedure system is illustrated in Figure 5.14.

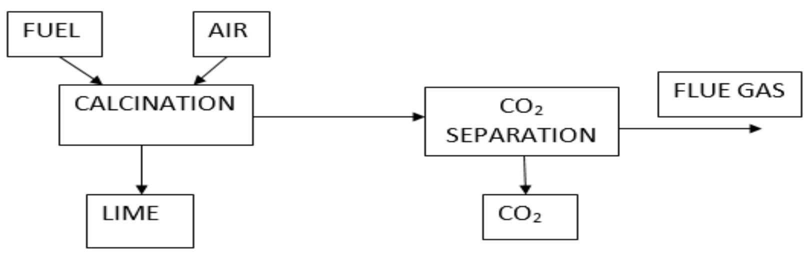


Figure 5.14: Schematic diagram of the post combustion process (Yang et al., 2008) .

Post-combustion decarbonisation in calcination is made up of two principal steps: calcining in which lime is created, then a CO_2 removal process in which a concentrated stream of CO_2 is brought about. This procedure has the best potential for diminishing GHG emissions, since it can be retrofitted to existing calcining plants (Figueroa et al., 2008). The main alternative is an assimilation procedure utilizing amine based solvents, for example Monoethanolamine ($H_2NCH_2CH_2OH$) (MEA) ingestion (Mikulčić et al., 2012). Other developing alternatives for post-combustion CO_2 capture are examined too.

5.2.9 Amine-Based Systems

Amines are chemically derived from ammonia (NH_3) and at least one of the hydrogen atoms is substituted by a carbon-based radical. For the most part, the formula for amines is R—NH_2. They exist as three types (primary, secondary, and tertiary), each with its good and bad as a CO_2 solvent. Classification of amines depends on the quantity of carbon-based clusters joined to the nitrogen atom.

Examples of amines include (Brady et al., 2002):

1. Methylamine, CH_3NH_2, a primary amine with one ammonia hydrogen substituted. It is in a gas form and dissolves in water and works in water solution. It is combustible, a 40% mixture having a flash point of – 7^oC, and its vapours are volatile in air. The vapours are broadly utilized as a source of nitrogen.
2. Dimethylamine, $(CH_3)_2NH$, a secondary amine. It forms a hydrate in water mixture, $(CH_3)_2NH \cdot 7H_2O$, that has a low point of solidification, – 16.8^oC.
3. Trimethylamine, $(CH_3)_3N$, a tertiary amine, is a gas that becomes a liquid at 2.87^oC.
4. Isopropylamine, $(CH_3)_2CNNH_2$, can replace ammonia in numerous chemical processes or as a solvent for oils, fats, and rubber. It is a transparent fluid of boiling point 31.9^oC, solidification point– 101^oC.
5. Sipenols are a collection of amines utilized as textile material oils and conditioners. They are clear to light yellow fluids and are dimethyl ethanol amines or dibutyl ethanol amines.

The majority of the amines have a strong rotting fish smell (Gershon and Ballinger 1990). Amines react with CO_2 to produce water soluble blends. Therefore, amines can capture CO_2

from streams of a low CO_2 pressure. In this way an amine-based scheme can collect CO_2 from the flue gas of the standard coal powered plants. A good benefit of this procedure is that it delivers a comparatively pure CO_2 stream (Yang et al., 2008). These schemes can be added to existing designs and reduce capital expenses. Such changes comprise adjusted tower packing that decrease pressure drop, expand energy consumption requirements to diminish vitality prerequisites, add substances to lessen corrosion and tolerate higher amine concentrations, and enhance recovery methods (Figueroa et al., 2008).

5.2.10 AEP (1-(2-Aminoethyl) Piperazine) Solution Compared to Primary, Secondary and Tertiary Amines

Different facets of CO_2 absorption, for instance, absorption volume, rate of absorption, required heat, wearing down of absorbent, and corrosion have been examined. Monoethanolamine (MEA), which is generally utilized commercially, displays a speedier reaction rate with CO_2 than other alkanolamine absorbents like diethanolamine (DEA), methyldiethanolamine (MDEA), and 2-amino-2-methyl-1-propanol (AMP).

More recently, a watery 1-(2-aminoethyl) piperazine (AEP) mixture was developed as a novel absorbent (Choi et al., 2016). It is a cyclic amine that incorporates a primary, a secondary, and a tertiary amino cluster in a molecule. The 1-(2-aminoethyl) piperazine particle shows wanted physical characteristics, for example, a high boiling point of 218-222^oC, low vapour pressure of 0.05 hPa at 22^oC and being completely miscible in water. It has been projected that a pioneering mix of piperazine with 1-(2-aminoethyl) piperazine displayed much higher absorbance for CO_2 capture (Du et al., 2013). It demonstrated high CO_2 collection and stable resistance to wearing out without the precipitation issue of highly concentrated piperazine.

5.2.11Rising Post-Combustion Innovations

Rising innovations are a mix of procedures that have illustrated enhancements in effectiveness and cost over the latest stage in the development of a procedure, consolidating the most up-to-date concepts and highlighting advancements. These may vary from real upgrades to existing procedures to exceptionally innovative methodologies(Figueroa et al., 2008). Examples are:

i. Carbonate-Based Systems

In carbonate systems, dissolvable carbonate can react with CO_2 to form a bicarbonate, and when the bicarbonate is heated it discharges the CO_2 and returns to a carbonate. A key benefit of carbonates over amine-based systems is that they essentially reduce energy required for recovery of the carbonate (Figueroa et al., 2008), (Rochelle et al., 2006).

ii. Aqueous ammonia

Ammonia-based systems function the same as amine systems. Ammonia and its subsidiaries react with CO_2. An example is ammonium carbonate, CO_2, and water reacting to form ammonium bicarbonate. This reaction saves energy since it requires less heat to react than amine-based systems only if the absorption/desorption cycle can be constrained to this system. Other benefits of ammonia-based over amine-based systems, may be: the potential for high CO_2 volume, absence of wearing off while absorption/recovery, tolerating oxygen in the flue gas and more(Figueroa et al., 2008).

iii. Membranes

Membranes may be used to capture CO_2 by having flue gas passing through a pile of membrane tubes, while an amine solution flows through the shell side of the pile. CO_2 at that point is absorbed into the amine, and impurities are stopped from being absorbed into the amine, thereby reducing the loss of amine because of stable salt development (Figueroa et al., 2008).

iv. CO_2 capture sorbents

Artefacts can be utilized to react with CO_2 to form steady compounds at a particular set of working environments and afterward be recovered to free the absorbed CO_2 and get back to the initial compound by adjusting that set of environments. However, solids are characteristically harder to work with than fluids, and no artefact sorbent system has been utilized commercially yet (Leung et al., 2014).

v. Enzyme-based systems.

Biological capture systems are another possible option of enhancing CO_2 capture. These depend on naturally happening reactions of CO_2 in living elements. One of these is the utilization of enzymes. An enzyme-based system accomplishes CO_2 capture and discharge by imitating the design of the mammalian respiratory framework (Figueroa et al., 2008).

5.2.12 Compression of the CO_2

Having captured the highly concentrated CO_2 stream it should be transported for underground storage or for CO_2 usage(Leung et al., 2014). In both cases CO_2 is needed at high pressure for transportation. Shipping requires that it be converted into liquid form (Feron and Hendriks 2005). One of the purposes of capturing CO_2 is to bring about a concentrated stream of CO_2 at high pressure for ease of transportation. It is important to produce an almost pure CO_2 stream for transportation and storage because transporting and injecting the full flue gas is unnecessarily expensive (Manovic and Anthony 2009).

5.3 Proposed Solutions to JMK Trading Company

5.3.1 Energy & Material Utilisation and CO_2 Capture

The most urgent requirement at JMK Trading Company is taking care of the environmental concerns. These will be achieved by minimising the emissions of greenhouse gases into the environment and aiming to reduce energy and material inputs. Safety of employees is of urgent concern too. The following are the proposed solutions to the company:

1. Addition of chimneys to the kilns. This will increase draught column hence preheating of limestone. The energy and material utilised will then reduce while achieving the same output.
2. Addition of an exhaust, the mechanism for collecting the flue gases. As the flue gas is collected it is made to pass through an amine system. Amines will react with CO_2 to form water soluble compounds. Thus, CO_2 is captured from the stream with a low CO_2 partial pressure. This technique will produce a relatively pure CO_2 stream. This will make the separation and collection of CO_2 becomes much more convenient. The AEP solution is giving hope of better CO_2 absorption properties, but more work is still being done on its physical properties.
3. Heat loss reduction will be achieved through the use of insulating materials such as vermiculite between the inner brick skin and outer brick layer. Energy utilisation is optimised this strategy.
4. Steel reinforcements to the kilns as shown in Figure 5.9 will assist in the sustainability of the kilns.

5. The grinding mill needs to be guarded for the health and safety of employees. The exposed belt is not safe for anyone working on the mill.

5.3.2 Uses of the Captured CO_2

After the capture of CO_2 it is crucial for the company to know how best to dispose of it and, most importantly, make some money out of it. Here are some proposals as to how CO_2 is used in industry hence making it easier to identify possible consumers (Gopito, 2016):

1. Multi-Industrial Uses – CO_2, as a solid or a fluid, is utilized for refrigeration and cooling
2. Metal Industries – CO_2 is utilized in casting processes to improve hardness.
3. Fabrication and Construction – CO_2 is utilized extensively as a shielding gas in some types of welding, where it guards the weld pool against oxidation by air. A blend of argon and carbon dioxide is normally utilized to accomplish a higher welding rates and lessen post weld treatment.
4. Chemicals, Pharmaceuticals and Petroleum Industries - Huge amounts of CO_2 are utilized as a raw material in the chemical procedure industry, particularly for methanol and urea generation.
5. Food and Beverages Industries - Liquid or solid CO_2 is utilized for rapid freezing, surface solidifying, cooling and refrigeration in food transportation. In cryogenic passage and winding coolers, high pressure fluid CO_2 is infused through spouts that change it to a blend of CO_2 gas and dry ice that covers the surface of the food items. As the dry ice changes from solid to gas, refrigeration gas is moved to the food item to solidify it. CO_2 is utilized to carbonate drinks, beers and wine and to avoid fungal and bacterial deterioration. Liquid carbon dioxide is utilized to de-caffeinate coffee, since it is a good solvent for many carbon compounds. The list of its applications in this industry is non-exhaustive.
6. Health Care – CO_2 is utilized as an additive to oxygen in medicine and as a breathing stimulator.
7. Miscellaneous Uses - Liquid CO_2 is a good solvent and for that reason, has been utilized in some laundry dry cleaning as a replacement for traditional solvents. This utilization is still being analysed as few kinds of soil are more successfully cleaned

off with conventional cleaning hardware, and the apparatus for use of CO_2 is more expensive.

These results were presented to the company for implementation, but due to financial constraints could not be implemented immediately. However, the results were kept securely for later implementation.

Chapter 6

CONCLUSION AND RECOMMENDATIONS

The main aim of this research was to contribute towards green manufacturing by identifying ways of improving environmental sustainability in the Zimbabwean steel industry. The research was carried out through literature search, industrial surveys that included interviews of key personnel and the use of a questionnaire, and experiments to verify a hypothesis that was formulated.

6.1 Research Outcomes

6.1.1 Literature Search

The literature search showed how much the production levels in the Zimbabwean steel industry have fluctuated over the years in line with changing conditions in the country's economy. This review explored green manufacturing and looked at the ways in which steel production has developed over the centuries in its two ways of manufacture namely: from its elements (the blast furnace way) and from scrap (the electric furnace way). Detailed literature search continued in each chapter specific to what was required as each chapter developed.

6.1.2 Industrial Surveys

The purpose of this survey was to come up with ways of ensuring sustainability. Literature search showed that sustainability stands on three pillars, namely: economic, social and environmental sustainability. The survey started off by identifying steel companies still active and visiting them to observe their operations, with keen interest in any measures put in place for sustainability. Interest in conserving the environment was shown in practices of these companies; however, not much improvement in that aspect was being concentrated on as the companies mostly battled to just survive economically. The Delphi approach was the most ideal in this survey. Interviews of key personnel in thirteen companies was the first round in the Delphi approach. It gave sensible direction on how economic sustainability may be achieved, which will in turn encourage companies to ensure social and environmental sustainabilities. These responses then shaped the questionnaire that was used to collect data that could be analysed. When it came to the second round of the Delphi approach, filling in the questionnaire, only twelve companies then participated. The main issue that all companies pointed to as the one to lead to economic sustainability was the change in policies making them friendlier to both local and foreign investors.

6.1.3 Experimentation

From the industrial survey three companies showed more interest in environmental sustainability and were willing to participate more fully in the research. Two of them (Craster International, in Harare and Midlands Metals, in Gweru) have landfills of the cupola furnace slag and wanted research done on how this waste product may be utilised. A similar waste product is blast furnace slag. Literature search showed that blast furnace slag has successfully been used in concrete making but very little success has been made in the use of cupola furnace slag in concrete making. An exciting hypothesis was formulated in the literature search that cupola furnace slag is chemically similar to Gehlenite, a mineral of the melilite group. Gehlenite has been successfully used as a lubricant in steel cutting. Chemical analysis confirmed this chemical similarity. Experiments were set up to analyse the behaviour of cupola furnace slag as a lubricant in the drilling of steel. Two sets of experiments were done on five brand new drill bits. Five lubricants were tested, the first was soluble oil as the control since it is the usual lubricant of choice at Craster International. The other four were the two samples of the cupola furnace slags in powder form and as pastes mixed in Vaseline. The results confirmed that generally cupola furnace slag is a possible lubricant in steel cutting, able to dissipate heat and provide some lubrication just as the soluble oil functions. The addition of Vaseline had few consequences; therefore it may be used in processes where the lubricant cannot work as a powder.

A third company was setting up calcination commercially. This process is of interest to this research since calcination is part of the process in the fabrication of steel from its elements. Initially the calcination was set up with no measure put in place to curb the greenhouse gas emissions. Specific research was done into ways of using less energy and clean the gases before they are released into the atmosphere and results presented to the company. The company is yet to apply these due to financial constraints.

6.2 Conclusions

The research was a success in coming up with practical ways of sustaining the environment.

i. Economic sustainability will provide a base for supporting environmental and social sustainability in many companies.
ii. The steel industry in Zimbabwe is operating at very low capacity when compared to international company utilisation or the operating capacity of steel production in other countries.
iii. The cost of electricity is a dominant input cost of the surveyed companies. National effort to reduce electricity cost or development of local electricity generation capacity could help economic sustainability.
iv. A significant number of the companies are addressing the challenges of reliable supply of water by harnessing ground water through borehole facilities.
v. A number of methods to improve the environmental sustainability of steel making operations were reviewed and it is noted that there is still a lot of potential for companies to apply the range of green technologies.
vi. There is a strong indication from the participants that the involvement by stakeholders or industry players in solving the problems facing the industry is a preferred option and that should be explored.
vii. A solution to the utilisation of cupola furnace slag was established. This will economically assist the companies by cutting out the purchases of soluble oil and commercialising the use of cupola furnace slag in cutting. Reduction of cupola furnace slag in landfills is a great contribution towards sustaining the environment and greener manufacturing.
viii. The research showed that 19%Si,13%Al,7%Ca slag may be used as a solid lubricant in dry drilling of steel. It is effective in drilling and outperformed oil-based cutting fluid when more boreholes are drilled. This can be attributed to its ability to act as a diffusion inhibitor and to elongate tool life. The 19%Si,13%Al,7%Ca slag had Aluminium and Silicon as the elements with the highest mass content. This makes its properties closer to those of Gehlenite than the 15%Si,8%Al,14%Ca slag properties.

This explains the better performance of 19%Si,13%Al,7%Ca slag than 15%Si,8%Al,14%Ca slag as a lubricant in steel cutting. The selection of slag that has a high aluminium and silicon content will help in its use as a cutting tool. It is also noted that both elements are key constituents of coatings for cutting tools.

ix. The use of cupola furnace slag in steel cutting is any easy and appealing solution for slag waste. Most importantly because it can be used as a powder lubricant directly from their landfills with minimum post processing. The only process that is required is grinding it to a powder form. The research can be taken further.

x. Application of greenhouse gas emissions mitigating measures by the calcination company will contribute immensely towards greener manufacturing.

6.3 Research Novelty

The main highlight of the research was the establishment of a new solution to the utilisation of cupola furnace slag. This will economically assist the companies by cutting out the purchasing of soluble oil and commercializing the use of cupola furnace slag in cutting. Reduction of cupola furnace slag in landfills is a great contribution towards sustenance of the environment leading to greener manufacturing. Promoting dry drilling will also advance sustainability by reducing the use of oil-based cutting fluids thus cutting costs and eliminating the environmental burden of oil usage.

During the industrial survey a number of methods to improve the environmental sustainability of steel making operations were reviewed and it is noted that there is still a lot of potential for companies to apply the range of green technologies. The companies are willing to apply these operations as soon as economic sustainability is established.

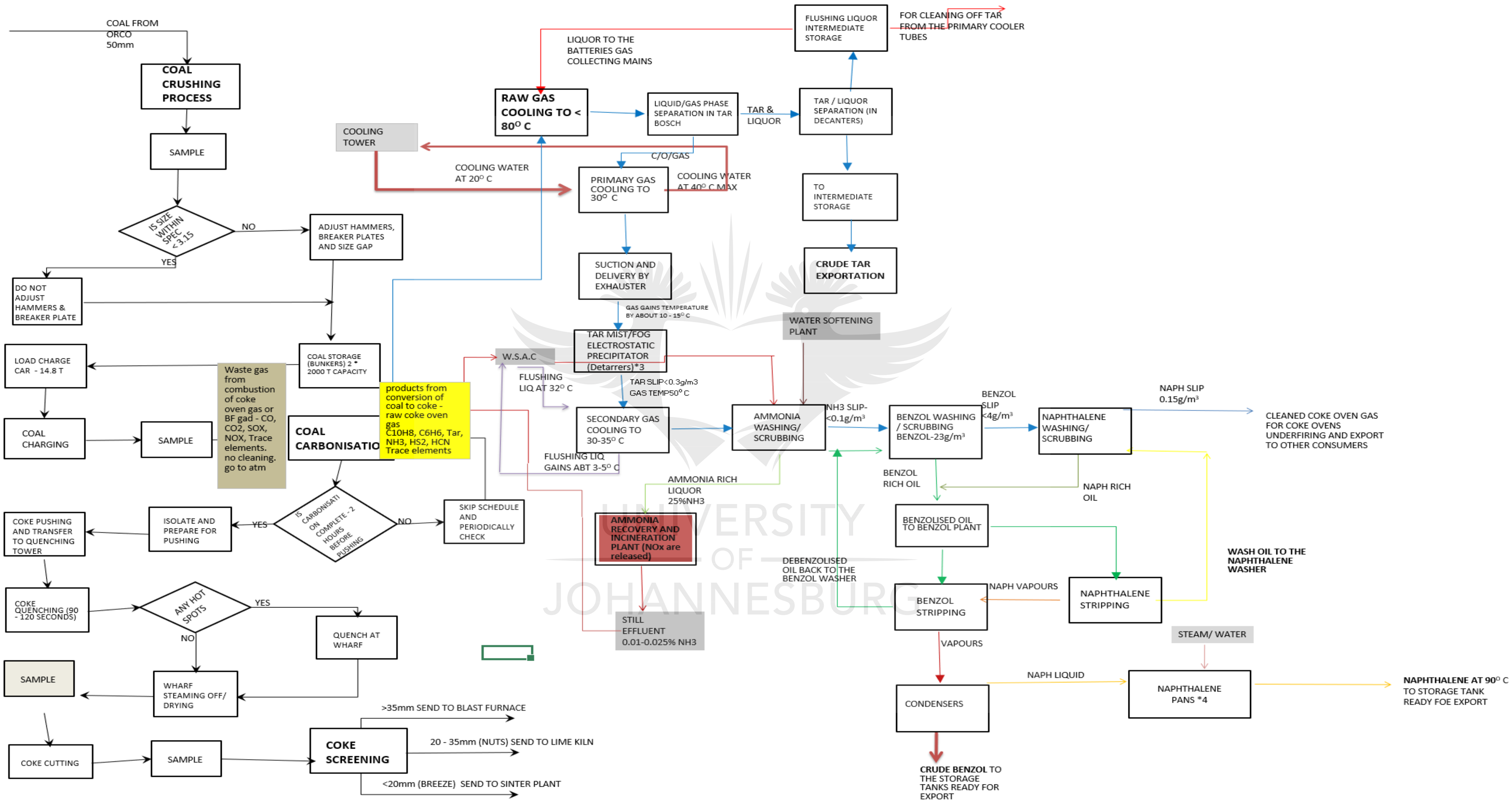
6.4 Recommendations for Further Work

Environmental sustainability is an ongoing discussion, especially in Zimbabwe. There is need to keep assessing many other processes and identifying ways of making them greener. Every opportunity to stop the release of greenhouse gas emissions or save the environment is important.

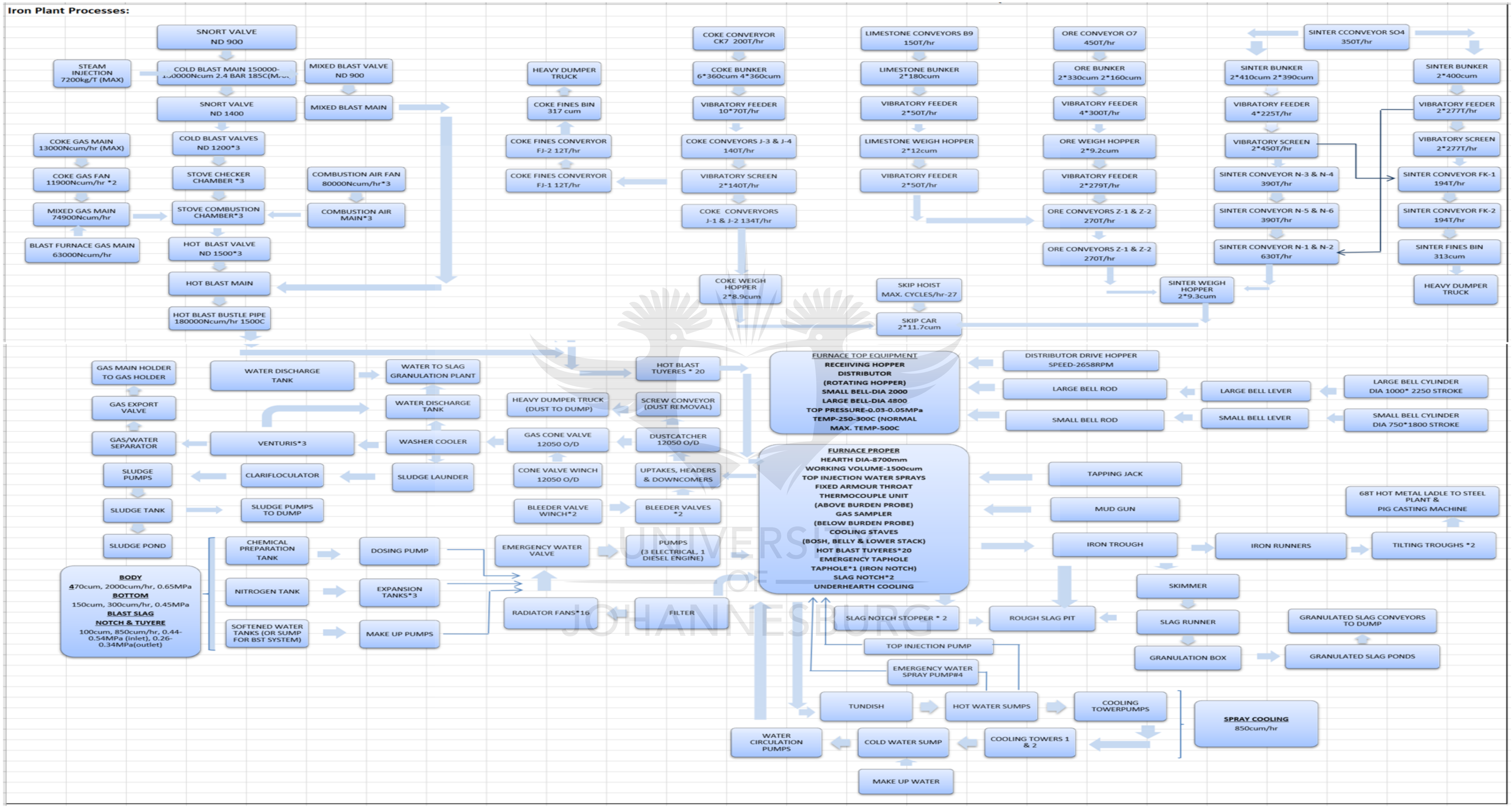
The research opens up new avenues to test the slag in drilling other workpiece materials, and in other cutting processes as well as optimising the powder morphology.

Application of recommendations made to JMKT company on making the Calcination process greener will add to the body of knowledge by identifying specific ways in which these methods can be applied to this particular case.

APPENDIX 3.1


COAL FROM ORCO 50mm
COAL CRUSHING PROCESS
SAMPLE
IS SIZE WITHIN SPEC < 3.15
NO
ADJUST HAMMERS, BREAKER PLATES AND SIZE GAP
YES
DO NOT ADJUST HAMMERS & BREAKER PLATE
COAL STORAGE (BUNKERS) 2 * 2000 T CAPACITY
LOAD CHARGE CAR - 14.8 T
Waste gas from combustion of coke oven gas or BF gad - CO, CO2, SOX, NOX, Trace elements. no cleaning. go to atm
COAL CHARGING
SAMPLE
COAL CARBONISATION
products from conversion of coal to coke - raw coke oven gas C10H8, C6H6, Tar, NH3, HS2, HCN Trace elements
IS CARBONISATION COMPLETE - 2 HOURS BEFORE PUSHING
YES
NO
SKIP SCHEDULE AND PERIODICALLY CHECK
ISOLATE AND PREPARE FOR PUSHING
COKE PUSHING AND TRANSFER TO QUENCHING TOWER
COKE QUENCHING (90 - 120 SECONDS)
ANY HOT SPOTS
YES
NO
QUENCH AT WHARF
SAMPLE
WHARF STEAMING OFF/ DRYING
COKE CUTTING
SAMPLE
COKE SCREENING
>35mm SEND TO BLAST FURNACE
20 - 35mm (NUTS) SEND TO LIME KILN
<20mm (BREEZE) SEND TO SINTER PLANT
COOLING TOWER
COOLING WATER AT 20° C
RAW GAS COOLING TO < 80° C
LIQUOR TO THE BATTERIES GAS COLLECTING MAINS
LIQUID/GAS PHASE SEPARATION IN TAR BOSCH
TAR & LIQUOR
TAR / LIQUOR SEPARATION (IN DECANTERS)
FLUSHING LIQUOR INTERMEDIATE STORAGE
FOR CLEANING OFF TAR FROM THE PRIMARY COOLER TUBES
C/O/GAS
PRIMARY GAS COOLING TO 30° C
COOLING WATER AT 40° C MAX
TO INTERMEDIATE STORAGE
CRUDE TAR EXPORTATION
SUCTION AND DELIVERY BY EXHAUSTER
GAS GAINS TEMPERATURE BY ABOUT 10 - 15° C
TAR MIST/FOG ELECTROSTATIC PRECIPITATOR (Detarrers)*3
W.S.A.C
FLUSHING LIQ AT 32° C
TAR SLIP<0.3g/m3 GAS TEMP50° C
SECONDARY GAS COOLING TO 30-35° C
FLUSHING LIQ GAINS ABT 3-5° C
WATER SOFTENING PLANT
AMMONIA WASHING/ SCRUBBING
NH3 SLIP- <0.1g/m³
AMMONIA RICH LIQUOR 25%NH3
AMMONIA RECOVERY AND INCINERATION PLANT (NOx are released)
STILL EFFLUENT 0.01-0.025% NH3
BENZOL WASHING / SCRUBBING BENZOL-23g/m³
BENZOL SLIP <4g/m³
NAPHTHALENE WASHING/ SCRUBBING
NAPH SLIP 0.15g/m³
CLEANED COKE OVEN GAS FOR COKE OVENS UNDERFIRING AND EXPORT TO OTHER CONSUMERS
BENZOL RICH OIL
NAPH RICH OIL
BENZOLISED OIL TO BENZOL PLANT
DEBENZOLISED OIL BACK TO THE BENZOL WASHER
WASH OIL TO THE NAPHTHALENE WASHER
BENZOL STRIPPING
NAPH VAPOURS
NAPHTHALENE STRIPPING
STEAM/ WATER
VAPOURS
CONDENSERS
NAPH LIQUID
NAPHTHALENE PANS *4
NAPHTHALENE AT 90° C TO STORAGE TANK READY FOE EXPORT
CRUDE BENZOL TO THE STORAGE TANKS READY FOR EXPORT

APPENDIX 3.2



Iron Plant Processes:
SNORT VALVE ND 900
STEAM INJECTION 7200kg/T (MAX)
COLD BLAST MAIN 150000-
MIXED BLAST VALVE ND 900
SNORT VALVE ND 1400
MIXED BLAST MAIN
COKE GAS MAIN 13000Ncum/hr (MAX)
COLD BLAST VALVES ND 1200*3
COKE GAS FAN 11900Ncum/hr *2
STOVE CHECKER CHAMBER *3
COMBUSTION AIR FAN 80000Ncum/hr*3
MIXED GAS MAIN 74900Ncum/hr
STOVE COMBUSTION CHAMBER*3
COMBUSTION AIR MAIN*3
BLAST FURNACE GAS MAIN 63000Ncum/hr
HOT BLAST VALVE ND 1500*3
HOT BLAST MAIN
HOT BLAST BUSTLE PIPE 180000Ncum/hr 1500C
HEAVY DUMPER TRUCK
COKE FINES BIN 317 cum
COKE FINES CONVERYOR FJ-2 12T/hr
COKE FINES CONVERYOR FJ-1 12T/hr
COKE CONVERYOR CK7 200T/hr
COKE BUNKER 6*360cum 4*360cum
VIBRATORY FEEDER 10*70T/hr
COKE CONVEYORS J-3 & J-4 140T/hr
VIBRATORY SCREEN 2*140T/hr
COKE CONVERYORS J-1 & J-2 134T/hr
COKE WEIGH HOPPER 2*8.9cum
LIMESTONE CONVEYORS B9 150T/hr
LIMESTONE BUNKER 2*180cum
VIBRATORY FEEDER 2*50T/hr
LIMESTONE WEIGH HOPPER 2*12cum
VIBRATORY FEEDER 2*50T/hr
SKIP HOIST MAX. CYCLES/hr-27
SKIP CAR 2*11.7cum
ORE CONVEYOR O7 450T/hr
ORE BUNKER 2*330cum 2*160cum
VIBRATORY FEEDER 4*300T/hr
ORE WEIGH HOPPER 2*9.2cum
VIBRATORY FEEDER 2*279T/hr
ORE CONVEYORS Z-1 & Z-2 270T/hr
ORE CONVEYORS Z-1 & Z-2 270T/hr
SINTER CCONVEYOR SO4 350T/hr
SINTER BUNKER 2*410cum 2*390cum
VIBRATORY FEEDER 4*225T/hr
VIBRATORY SCREEN 2*450T/hr
SINTER CONVEYOR N-3 & N-4 390T/hr
SINTER CONVEYOR N-5 & N-6 390T/hr
SINTER CONVEYOR N-1 & N-2 630T/hr
SINTER WEIGH HOPPER 2*9.3cum
SINTER BUNKER 2*400cum
VIBRATORY FEEDER 2*277T/hr
VIBRATORY SCREEN 2*277T/hr
SINTER CONVEYOR FK-1 194T/hr
SINTER CONVEYOR FK-2 194T/hr
SINTER FINES BIN 313cum
HEAVY DUMPER TRUCK
GAS MAIN HOLDER TO GAS HOLDER
GAS EXPORT VALVE
GAS/WATER SEPARATOR
SLUDGE PUMPS
SLUDGE TANK
SLUDGE POND
WATER DISCHARGE TANK
WATER TO SLAG GRANULATION PLANT
WATER DISCHARGE TANK
VENTURIS*3
WASHER COOLER
CLARIFLOCULATOR
SLUDGE LAUNDER
SLUDGE PUMPS TO DUMP
HEAVY DUMPER TRUCK (DUST TO DUMP)
GAS CONE VALVE 12050 O/D
CONE VALVE WINCH 12050 O/D
BLEEDER VALVE WINCH*2
HOT BLAST TUYERES * 20
SCREW CONVEYOR (DUST REMOVAL)
DUSTCATCHER 12050 O/D
UPTAKES, HEADERS & DOWNCOMERS
BLEEDER VALVES *2
BODY
470cum, 2000cum/hr, 0.65MPa
BOTTOM
150cum, 300cum/hr, 0.45MPa
BLAST SLAG
NOTCH & TUYERE
100cum, 850cum/hr, 0.44-0.54MPa (inlet), 0.26-0.34MPa(outlet)
CHEMICAL PREPARATION TANK
NITROGEN TANK
SOFTENED WATER TANKS (OR SUMP FOR BST SYSTEM)
DOSING PUMP
EXPANSION TANKS*3
MAKE UP PUMPS
EMERGENCY WATER VALVE
PUMPS (3 ELECTRICAL, 1 DIESEL ENGINE)
RADIATOR FANS*16
FILTER
FURNACE TOP EQUIPMENT
RECEIIVING HOPPER
DISTRIBUTOR
(ROTATING HOPPER)
SMALL BELL-DIA 2000
LARGE BELL-DIA 4800
TOP PRESSURE-0.03-0.05MPa
TEMP-250-300C (NORMAL
MAX. TEMP-500C
DISTRIBUTOR DRIVE HOPPER SPEED-2658RPM
LARGE BELL ROD
LARGE BELL LEVER
LARGE BELL CYLINDER DIA 1000* 2250 STROKE
SMALL BELL ROD
SMALL BELL LEVER
SMALL BELL CYLINDER DIA 750*1800 STROKE
FURNACE PROPER
HEARTH DIA-8700mm
WORKING VOLUME-1500cum
TOP INJECTION WATER SPRAYS
FIXED ARMOUR THROAT
THERMOCOUPLE UNIT
(ABOVE BURDEN PROBE)
GAS SAMPLER
(BELOW BURDEN PROBE)
COOLING STAVES
(BOSH, BELLY & LOWER STACK)
HOT BLAST TUYERES*20
EMERGENCY TAPHOLE
TAPHOLE*1 (IRON NOTCH)
SLAG NOTCH*2
UNDERHEARTH COOLING
TAPPING JACK
MUD GUN
68T HOT METAL LADLE TO STEEL PLANT & PIG CASTING MACHINE
IRON TROUGH
IRON RUNNERS
TILTING TROUGHS *2
SKIMMER
SLAG NOTCH STOPPER * 2
ROUGH SLAG PIT
SLAG RUNNER
GRANULATED SLAG CONVEYORS TO DUMP
TOP INJECTION PUMP
EMERGENCY WATER SPRAY PUMP#4
GRANULATION BOX
GRANULATED SLAG PONDS
TUNDISH
HOT WATER SUMPS
COOLING TOWERPUMPS
SPRAY COOLING
850cum/hr
WATER CIRCULATION PUMPS
COLD WATER SUMP
COOLING TOWERS 1 & 2
MAKE UP WATER

PUBLICATIONS BASED ON THE RESEARCH

JOURNAL PAPERS

1. **Gudukeya L.,** Mbohwa C., Mativenga P.T.: Deriving Value from Waste: Blast Furnace Slag as a Solid Lubricant in Drilling Processes. Journal of Advanced Manufacturing Technology (2018). Still under review

Conference Papers:

1. **Gudukeya L.,** Mbohwa C Survey on Greenhouse Gas Emissions in the Steel Industry in Zimbabwe. *International Association of Engineers World Congress on Engineering* at London, U.K., 1-3 July, 2015

2. **Gudukeya L**., Mativenga P., Sustainability for the Manufacturing and Service Industries in Zimbabwe. *2017 International Symposium on Industrial Engineering and Operations Management (IEOM)* at Bristol, UK, July 24-25, 2017. Pages 364 375. **ISBN: 978-1-5090-3924-1**

3. **Gudukeya L**., Mbohwa C., Environmental Sustainability: Abatement of CO_2 Emissions from a Calcination Plant in Zimbabwe. *2017 International Conference on Industrial Engineering and Operations Management* at Bogota, Colombia, October 25-26, 2017. Pages 1077 – 1088. **ISBN: 978-1-5323-5943-9**

4. **Gudukeya L.,** Mbohwa C., Mativenga P.T.: Industrial Sustainability in a Challenged Economy: The Zimbabwe Steel Industry. 16th Global Conference on Sustainable Manufacturing, Lexington Kentucky, USA, 2-4 October, 2018.

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