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BENCHMARKING SMELTING PRODUCTION PROCESSES OF MANGANESE FERROALLOYS

Boitshoko Kaelo Sedumedi

UNIVERSITY
2019
JOHANNESBURG
Declaration of Authenticity

I hereby declare that the thesis for MTech: Extraction Metallurgy, **BENCHMARKING SMELTING PRODUCTION PROCESSES OF MANGANESE FERROALLOYS** submitted to the University of Johannesburg, apart from the help recognised, is my own work and has not previously been submitted to another university or institution of higher education for a degree. Each source of information used has been acknowledged by means of a complete reference.

Signed at Johannesburg on this 05th day of June 2019.

Signature: …………………………….

Name: Boitshoko Kaelo Sedumedi

Johannesburg, South Africa

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I agree that I have read and that I understand the copyright notice.
Acknowledgements

The study is innately dedicated to those very close to me, especially my late parents, Mr Tsienyane E. Sedumedi and Mrs Kelepile M. Sedumedi as well as to my two late siblings, Mr Kgoiolo T. Sedumedi and Ms Dineo M. Sedumedi. My parents instilled in me the values of hard work, persistence, learning and self-development.

It was not going to be possible to undertake the research study without the critical assistance of my supervisor, Dr Xiaowei Pan. His global insights and theoretical inputs on the production of manganese ferroalloys were very unique and made this academic and practical undertaking very enjoyable. Therefore the study was conceptually richer with his important technical and metallurgical dimensions to make this unique academic undertaking as close to reality as possible.

Lastly, I am greatly thankful to the general managers and plant engineers from the plants that were investigated, together with their organisations’ plant processes used as reference cases for this thesis; and the other assessed organisations. Without them, the content will definitely have been less technically plausible from the actual and current practices in the smelting processes for the production of manganese ferroalloys.
Synopsis

The study made a global examination of how smelting technologies are employed in the production of manganese ferroalloys. Focus was placed on the technological production processes that the various smelters used with the accompanying aspects like manganese ore preparation, crushing, screening, furnace operations and the cooling operations. Certain criteria were taken as a given like the ISO9000 and ISO1400 accreditation. Various production and smelting methods were globally used depending on the raw materials being fed, importantly the manganese ore composition and reductants like anthracite and coke.

It was prudent for any metallurgical practice to look at how manganese ferroalloys can be produced efficiently. In benchmarking the smelting production processes, the basis of comparative analysis included both the effectiveness and efficiency of production as depended upon the identified major factors: manganese ore type and preparation, furnace operations, tapping and cooling operations, and alloy packaging and storage. The study made an evaluation of the observed smelting processes against the critical key performance indicators like quality/specifications, cost, flexibility, delivery time and other economic imperatives. The electricity was taken as a constant since the output manganese ferroalloy production capacity was preset in most of the plants. Hence the most important aspect the study examined closely in benchmarking was the smelting input materials combination.

Summarily, the study identified the most critical aspects that required technical consideration for benchmarking in the production processes of manganese ferroalloys. The critical aspects were the following: the general plant production context, production monitoring, accountability on the production unit, and the process predictability. In the final analysis, the following were recommendations to be considered: better treatment of low Mn grade ores, improvements in process control and specific situational monitoring, specific considerations on mineralogical applications, alternation of process methods like blast furnace, DC arc furnace and granulation of final products instead of billeting.
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<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
<td></td>
</tr>
<tr>
<td>AE</td>
<td>Allocation Efficiency</td>
<td></td>
</tr>
<tr>
<td>AMSA</td>
<td>Arcelor Mittal South Africa</td>
<td></td>
</tr>
<tr>
<td>BF</td>
<td>Blast Furnace</td>
<td></td>
</tr>
<tr>
<td>CCTV</td>
<td>Closed Circuit Television</td>
<td></td>
</tr>
<tr>
<td>CE</td>
<td>Cost Efficiency</td>
<td></td>
</tr>
<tr>
<td>ChCr</td>
<td>Charge Chrome</td>
<td></td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
<td></td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier Transform Infrared spectroscopy</td>
<td></td>
</tr>
<tr>
<td>HCFeCr</td>
<td>High Carbon Ferrochrome</td>
<td></td>
</tr>
<tr>
<td>HCFeMn</td>
<td>High Carbon Ferromanganese</td>
<td></td>
</tr>
<tr>
<td>ICMMME</td>
<td>International Conference on Mining, Mineral Processing and Metallurgical Engineering</td>
<td></td>
</tr>
<tr>
<td>INFACON</td>
<td>International Ferroalloys Congress</td>
<td></td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
<td></td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
<td></td>
</tr>
<tr>
<td>LCFeCr</td>
<td>Low Carbon Ferrochrome</td>
<td></td>
</tr>
<tr>
<td>LCFeMn</td>
<td>Low Carbon Ferromanganese</td>
<td></td>
</tr>
<tr>
<td>LGRO</td>
<td>Low Grade Rhodochrosite Ore</td>
<td></td>
</tr>
<tr>
<td>LTIFR</td>
<td>Lost Time Injury Frequency Rate</td>
<td></td>
</tr>
<tr>
<td>MCFeMn</td>
<td>Medium Carbon Ferromanganese</td>
<td></td>
</tr>
<tr>
<td>MRP</td>
<td>Metal Recovery Plant</td>
<td></td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
<td></td>
</tr>
<tr>
<td>R/t</td>
<td>Rands per tonne</td>
<td></td>
</tr>
<tr>
<td>RSA</td>
<td>Republic of South Africa</td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>Run of Mine</td>
<td></td>
</tr>
<tr>
<td>SAF</td>
<td>Submerged Arc Furnace</td>
<td></td>
</tr>
<tr>
<td>SDA</td>
<td>Secondary Data Analysis</td>
<td></td>
</tr>
<tr>
<td>SEM</td>
<td>Scanned Electron Microscope</td>
<td></td>
</tr>
<tr>
<td>SiMn</td>
<td>Silico-manganese</td>
<td></td>
</tr>
<tr>
<td>TE</td>
<td>Technical Efficiency</td>
<td></td>
</tr>
<tr>
<td>TMC</td>
<td>Total Manganese Content</td>
<td></td>
</tr>
<tr>
<td>tpa</td>
<td>tonnes per annum</td>
<td></td>
</tr>
<tr>
<td>tpd</td>
<td>tonnes per day</td>
<td></td>
</tr>
<tr>
<td>UC</td>
<td>Unit Cost</td>
<td></td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
<td></td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Service</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>United States of America</td>
<td></td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray Diffraction</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Background

Ferromanganese (FeMn/SiMn) is produced through the carbothermal reduction of manganese (Mn) ores, primarily in electric submerged arc furnaces. In this study ferromanganese would refer to low, medium, and high carbon ferromanganese (LC/MC/HCFeMn), and silicomanganese (SiMn). Manganese (Mn) plays a crucial role in the iron and steel industry. As an alloying element, it improves the strength, toughness, hardenability, workability and abrasion resistance of the ferrous products, especially steel. A paper was published and presented in April 2014 at the International Conference on Mining, Mineral Processing and Metallurgical Engineering (ICMMME) to address the benchmarking techniques in the production of manganese ferroalloys production (Sedumedi and Pan, 2014)**.

About 90 – 95% of all the manganese produced in the world is used in iron and steel production in the form of alloys such as ferromanganese (FeMn) and silicomanganese (SiMn). Manganese has two important properties in steelmaking: its ability to combine with sulphur to form manganese sulphide (MnS) and its deoxidation capacity. Today about 30% of the manganese used in steel industry is used for its properties as a sulphide former and deoxidant. The other 70% of the manganese is used purely as an alloying element.

South Africa is a significant producer of Mn ore, exporting most of its manganese ore as per Figure 1.1, and thus beneficiating very little into ferromanganese. It is the second biggest producer of Mn ore in terms of Mn content or Mn units. Very little comparative advantage is translated into competitive advantage. Factors being attributed to are the price of electricity, and lack of access by the current ferromanganese producers to good quality Mn ore reserves. In the 1980s, the top six ferromanganese-producing countries in the world were in decreasing order of production China, South Africa, Ukraine, Kazakhstan, Russia, and Norway. The USA and France were the other countries just in the margins (Jones, 1994). South Africa has since been surpassed by Norway and India. It would be important to understand the challenges of ferromanganese production in South Africa to make it competitive given that South Africa has 80% of the known manganese reserves in the world (Sedumedi and Pan, 2014)**.

**From a paper titled “Improve Ferromanganese Smelting Processes Using Benchmarking Techniques” published and presented at the International Conference on Mining, Mineral Processing and Metallurgical Engineering (ICMMME 2014) held in Johannesburg, South Africa on 15-16 April 2014**
Ferromanganese consumption can be taken as proportional to the production of raw steel. The most common ferromanganese is high-carbon ferromanganese and is referred to as standard ferromanganese, and silicomanganese. Silicomanganese became widely used with the invention of secondary production of steel through recycling processes by American steel producers in the 1960s. Maintaining control of the addition and consumption of carbon is perhaps the most important issue for the operation of an electric submerged arc furnace.
Manganese ores are classified according to their contents of manganese. In general, ores containing at least 35% manganese are classified as manganese ores. Ores having 10–35% Mn are known as ferruginous manganese ores, and ores containing 5–10% manganese are known as manganiferrous ores. Ores containing less than 5% manganese with the balance mostly being iron are classified as iron ores. Manganese ores are also classified as metallurgical, battery and chemical quality ores. Metallurgical ore is used in ferromanganese or special manganese alloy production or as chemicals. Battery ores are natural or artificial. They are manganese oxides with various purities. Chemical quality manganese ores are classified as group A or group B depending on their manganese, iron and silica contents (Jones, 1994; Olsen et al, 2007).

1.2 Technical Problem

The study seeks to formulate how benchmarking methods can be used in the efficient and effective production of manganese ferroalloys (FeMn/SiMn). Relevant indicators related to the production technologies have to be identified within the manganese ferroalloys process environment. Various smelters have different production parameters in terms of the type of ores used, reductant types, furnace sizes, cooling methods employed, and storage methods. There has never been an initiative by experts to formulate the most relevant or optimal production parameters and/or variables within the manganese ferroalloys smelters.

Benchmarking is recognised as an essential tool for continuous improvement of the quality of products. It is a process that will allow the production of manganese ferroalloys (FeMn/SiMn) to improve upon existing ideas and practices. In order to eliminate myths and misconceptions about benchmarking, it is important to know exactly what the relevance of benchmarking is - the different types of benchmarking, the criticisms of benchmarking, and the techno-ethical practices formed. The principles of benchmarking have to be counterposed with the intrinsic economic aspects of the ferromanganese operations.

Some of the most important broad aspects to be considered for counterposing benchmarking against the ferromanganese production processes: transport, raw materials – manganese ores, reductants, fluxes, raw materials handling and storage, handling procedures, furnaces’ operations, air pollution control equipment, product handling and storage, energy considerations, occupational health and safety, labour, and management and monitoring procedures.
Alternative materials, principally alloy scrap and oxide, have gained moderately on ferromanganese use per tonne of steel produced during the decade starting from the 1990s. A decline in the unit consumption is significant over the long term for the ferromanganese industry because such a decline moderates any increase in ferromanganese consumption resulting from increased steel production. A combination of factors, including technology, availability, and price, is responsible for this general decline in unit consumption of the major ferroalloys in steelmaking, particularly the production of ferromanganese. Customer needs for FeMn/SiMn in alloy and stainless steel for many applications have been and will continue to be strong.

The steel industry continues to improve processing technology to reduce raw material needs and develop steel grades with lower alloying metal content, which equals or betters performance, while lowering materials costs. For many steel applications, there are no acceptable substitutes, and their key constituents, high-carbon ferromanganese and silicomanganese, are essential. As technology and industry practices result in more efficient use of ferroalloys, strong demand for metals in construction, the chemical industry, transportation, and household appliances is expected to more than offset any basic reduction in unit consumption. Competition from other materials, such as plastics and nonferrous metals in the transportation sector, would be strong, but the use of lightweight and high-strength steel is expected to keep the ferroalloys industry competitive for many years.

Various types of benchmarking techniques have been identified in the past, and there are three primary types that are in use today. These are process benchmarking, performance benchmarking, and strategic benchmarking. Process benchmarking focuses on the day-to-day operations of the ferromanganese facility. It has the primary concern of improving the way processes are performed day by day. Some examples of work processes that could utilise process benchmarking are the customer complaints or inputs process, the delivery timing of ferromanganese product, the order fulfillment process, and the recruitment process. All of these processes are at the front end of the organisation of the production facility. By making improvements at a lower level, performance improvements are quickly realised. This type of benchmarking results in quick improvements to the organisation of production particularly the servicing aspects.
Performance benchmarking focuses on assessing competitive positions through comparing the products and services of other competitors. When dealing with performance benchmarking, organisations want to look at where their product or services are in relation to competitors on the basis of things such as reliability, quality, speed, and other product or service characteristics. Here a ferromanganese production facility would adopt the reverse engineering methods of understanding the competitors’ products.

Strategic benchmarking deals with the leadership dimension in the production equation. It mostly deals with long-term results. Strategic benchmarking could focus on how the production facilities compete. This form of benchmarking looks at what strategies the facilities are using to make them successful. This is the type of benchmarking technique that most Chinese and Japanese facilities use (Bogan, 1994). This is due to the fact that these facilities focus on long-term results and sustainability.

Figure 1.5: Ferromanganese production scenarios

In general the benchmarking scope in terms of the types is as follows (Ajelabi and Tang, 2010):

<table>
<thead>
<tr>
<th>Benchmarking Type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance Benchmarking</td>
<td>It is the comparison of performance measures for the purpose of determining how good an organisation is in comparison to others</td>
</tr>
<tr>
<td>Process Benchmarking</td>
<td>It is the comparison of methods and processes in an effort to improve the processes in a smelting plant</td>
</tr>
<tr>
<td>Strategic Benchmarking</td>
<td>It is the comparison of an organisation’s strategy with successful strategies from other organisations to help</td>
</tr>
</tbody>
</table>
improve capability to deal with a changing external environment

**Competitive Benchmarking**
This is the comparison made against the “best” competition in the same market to compare performance and results.

**Functional Benchmarking**
It is comparisons of a particular function in an industry. The purpose of this type of benchmarking is to become the best in the function.

**Internal Benchmarking**
It is the comparisons of performance made between department/divisions of the same organisation solely to find and apply best practice information.

**Generic Benchmarking**
It is the comparison of processes against best process operators regardless of industry.

The systematic discipline of benchmarking is focused on identifying, studying, analysing, and adapting best practices and implementing the results. To consistently get the most value from the benchmarking process, the leadership could discover the need for a significant culture change. Such change, however, unleashes benchmarking’s full potential to generate large operational and strategic advantage. The benchmarking process involves comparing one facility’s performance on a set of measurable parameters of strategic importance against that of facilities’ known to have achieved best performance on those indicators. Development of benchmarks is an iterative and ongoing process that is likely to involve sharing information with other ferromanganese production facilities working with them towards an agreeable paradigm of operations and/or co-production processes.

Most benchmarking as per the existing known information, have historically focused on the following organisational and operational areas:

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Education</td>
<td>5%</td>
</tr>
<tr>
<td>Innovations and Case Studies</td>
<td>7%</td>
</tr>
<tr>
<td>Specific Applications/Case Studies</td>
<td>43%</td>
</tr>
<tr>
<td>General/Fundamentals/Models</td>
<td>45%</td>
</tr>
</tbody>
</table>

The challenge of benchmarking within the ferromanganese production facilities is apparent noting very limited work done on innovation and learning elements within and amongst facilities and organisations. Or at least very little has been recorded to assist in the attainment of understanding how the ferromanganese production is benchmarked. Only one major benchmarking study was encountered, which was comparing the production capabilities using DC submerged arc furnace and the AC
submerged electric arc furnace by Mintek in 2010. The targeted element was to be efficient with electricity use and the attainment of better economies of scale as the end result of the FeMn production process.

When a ferromanganese production facility looks at benchmarking, it must interrogate all aspects of the business, its products, and its processes. It is crucial for a production process or operation to focus on anything that would impact on its efficiency, performance, growth and quality. The initial method used for ferromanganese production was the blast furnace whereby the USA was a leading producer before 1945. It only produced the high carbon ferromanganese (HCFeMn) and consumed a lot of reductant per metal produced because the carbon source was both a source of power and a reductant. Hence there was a move to roll-out submerged electric furnaces (SAF).

From 1977 the USA imported manganese only in the form of ferromanganese and manganese metal. Nowadays, even with the production paradigm of the submerged electric arc furnaces, there are moves to find the most efficient and economic production method of ferromanganese. Hence there is a need to understand how to influence the process of improving performance by continuously identifying, understanding, and adapting the outstanding practices and processes found inside and outside an organisation i.e. benchmarking.

Figure 1.3: Typical ferromanganese production furnace (courtesy Olsen et al, 2007)
By 2005, 75% of the production of manganese ferroalloys (FeMn/SiMn) was done through the electric arc furnaces as depicted in Figure 1.3 as compared to the blast furnace. The shift away from blast furnaces was due to the expensive coke, and the lower capital investment required for electric arc furnaces. So technology choices are important in determining new FeMn/SiMn production processes. However, in determining the specific technology and technique of ferromanganese production benchmarking, there is a need to identify the production drivers. The drivers have previously been broadly identified as thermodynamic factors, delivery factors, and leadership elements.

A technique can be developed from the identification of drivers and new indicators from what is generally known. In considering the thermodynamic issues, each broad parameter like reductant availability, can be cascaded further into sub-categories like reductant sourcing, reductant preparation and reductant blending. The same can be said with electricity usage that can be controlled when similar operators collaborate, as there are a handful of meaningful players in the industry. Rotational toll smelting can be considered in the future to bring the production costs down.

Previous studies have resulted in the identification of benchmarking matrix as below, and considered the development of any sub-categories and indicators for focused parameter controlling. Some of the technique elements to be factored in the production process would be the following:

- Minimal pre-treatment of some feedstock like reductants for better porosity;
- Charge stepped-up treatment in multiple furnaces;
- Blending of charge from different ore bodies;
- Blending of reductant of different specifications for process optimisation;
- Maintaining consistent temperature levels at secondary furnaces and ladles for improved metal recovery and electricity saving;
- The use of aluminium oxide to increase manganese recovery from the slag; and
- Better preparation of slags as feed material.

There are five cyclic phases for implementation of benchmarking referred to as the Deming cycle (Kelessidis, 2000; Ajelabi and Tang, 2010):
A. PLANNING
During this phase the FeMn operation determines which process to benchmark and against what type of smelting plant or organisation.

B. ANALYSIS
Following data acquisition, an analysis is performed for the performance gap between the source organisation and the recipient organisation. An indication of best practice is then evident.

C. INTEGRATION
It involves the preparation of the recipient for implementation of actions.

D. ACTION
This is the phase where the actions are implemented within the recipient production process or operation.

E. MATURITY
This involves continuous monitoring of the process and enables continuous learning and provides input for continuous improvement within the recipient production process.

1.3 Objectives of research

1.5.1 Overview
As stated before, South Africa has the largest reserves of Mn ore in the world i.e. eighty percent (80%) of reserves. What has been asked is whether South Africa derives real benefit for being in possession of these large manganese reserves. The beneficiation of manganese ores is done by producing the manganese ferroalloys through the carbothermal reduction of manganese ores. In South Africa, the size of the manganese ores reserves is indirectly proportional to the ferromanganese production by the existing facilities or smelters. The primary objective of the study is to interrogate how through benchmarking techniques the production of manganese ores can be directly proportional to the production of manganese ferroalloys. In this context, the unit of analysis will be a FeMn/SiMn production process in a production facility or smelter. Therefore the research question would be: What are the benchmarking techniques that can be used in the production of manganese ferroalloys, in this instance ferromanganese (FeMn) and Silicomanganese (SiMn)?
It has been observed that the production of high quality FeMn/SiMn has become increasingly important in the context of fluctuations in the iron ore price in global markets. Manganese ore prices are closely associated with those of iron ore prices. In appreciating the importance of benchmarking the various ferromanganese production practices worldwide, such practices have to be identified to develop methodological aspects. Firstly, the standard production variables would be reconfirmed, and identify new ones given the various sophisticated production environments. In other words, are there unique variables to specific production facilities? Secondly, appropriate benchmarking method(s) could be recommended given the production objectives in existence. Inductively, all the variables, both metallurgical and non-metallurgical would be condensed into a concept or particular benchmarking techniques or indicators.

Benchmarking can be perceived from various parameters from which the operational SiMn/FeMn facility functions. These parameters are aligned to the benchmarking type i.e. process, performance and strategic benchmarking. In addition, any considerations of any parameter elements have to be aware of the context of application of the ferromanganese operations globally. The context is largely defined by striving for efficiency in production processes, improved performance, and the growth of the production facilities (Boxwell, 1994).
Hence the following benchmarking matrix could be developed for the production of ferromanganese alloys:

Table 1.2: Benchmarking Matrix

<table>
<thead>
<tr>
<th>Process</th>
<th>Performance</th>
<th>Strategic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer inputs</td>
<td>Furnaces</td>
<td>Industry co-operations</td>
</tr>
<tr>
<td>Transport</td>
<td>Energy</td>
<td>Quality standards</td>
</tr>
<tr>
<td>Handling procedures</td>
<td>Raw materials-ore, reductants, and fluxes</td>
<td>Managerial leadership</td>
</tr>
<tr>
<td>Labour</td>
<td>Air pollution control equipment</td>
<td>Monitoring procedures</td>
</tr>
<tr>
<td>Delivery time</td>
<td>Flexibility</td>
<td>Cost</td>
</tr>
<tr>
<td>Reliable FeMn production</td>
<td>Material handling strategies</td>
<td>Technology</td>
</tr>
</tbody>
</table>

From the above benchmarking matrix, various production elements are identified and observed. And the most influential ferromanganese production elements can be the following:

**1.5.2 Input materials**

One of the most important input elements are reductants, which are mostly coke, coking coal and anthracite. These elements influence the thermodynamics and eventually contribute to the efficiency of the FeMn production process. Some organisations have developed special expertise to optimise the fixed carbon content for reduced electricity consumption. Equally important is the preparation by some FeMn operations of anthracite through further crushing to the required specification required. Most elements associated with input materials would fall under the categories of process and performance benchmarking.

**1.5.3 Process thermodynamics physico-chemical elements:**

Ferromanganese production facilities should continuously identify new indicators of making their operations competitive. There are certain techniques that can be exploited which are fully utilised by the ferroalloy production facilities like ferronickel, ferrovanadium and ferrochrome. Very little toll smelting is undertaken in the ferromanganese production. And it can assist in the high economies of scale, as there will be more access to the manganese ore. The proposed Coega ferromanganese would operate along similar lines. Toll smelting could be used by individual ferromanganese operators either on a rotational basis on existing facilities or establish new central facilities. Elements associated with the process
thermodynamics would largely fall under the category of performance benchmarking (Steenkamp, 2012).

1.3.4 Co-production initiatives:
It is usually not a practice in the production of FeMn for organisations to share facilities for production. But as is customary, there are company buy-ins, investments and divestments to allow newer investing organisations, and cross-shareholderships. For the FeMn players, most of the cross-shareholding is done to access the manganese ore and for co-marketing purposes. And it is not done for co-production. The co-marketing is an inference used to observe the investors’ orientation as in the mining and beneficiation of heavy sands in South Africa by the mining major organisations.

The ferromanganese production requires continuous benchmarking through the identification of indicators to fit into the already known production aspects. Such indicators would relate to each of the production elements, and hence the benchmarking types in the production of ferromanganese alloys. Benchmarking benefits are illustrated by the two most important determinants of FeMn/SiMn production: availability of electricity, suitable Mn ores and reductants. The operations of ferromanganese production facilities face huge challenges of input costs. These costs attest to the fact that inputs like electricity provision was in the past almost guaranteed at subsidised levels. But such arrangements between the power generation authorities and FeMn/SiMn production facilities cannot hold in the face of globalisation and competition. Governments are also competing for investments into their countries with ever increasing population sizes. Hence the competition of energy resources between communities and the FeMn/SiMn production facilities has resulted with opposition to electricity tariffs. In South Africa, ESKOM has a buy-back arrangement with ferroalloy smelters during the winter months to offset the availability of electricity to other social and community needs.

It can also be pointed out that the source of excellent reductants is getting fewer as years pass by. An observation made is that the mining of anthracite and coking coal is usually under difficult conditions particularly if large volumes are required. For safety considerations, mines produce volumes not necessarily meeting the entire needs of the FeMn/SiMn production facilities, and the ferroalloy industry in general. Hence there is a practice of multi-sourcing from various mines throughout the world. In South Africa, smelters source the reductants from Swaziland, South Africa,
Zimbabwe and Ukraine. There is a sense of urgency to fast-track innovation and learning by the FeMn facilities. It is noted that most benchmarking efforts have been on developing general models and specific applications. And it is an existing reality within the ferromanganese industry. Very little attention has been paid into refinement of processes and the eventual product development.

Benchmarking in the FeMn/SiMn production facilities will assist in developing discipline, systematic processes of what can work. It will provide a sense of urgency to get a change effort off the ground. With better focus, the industry will pinpoint on developing and improving specific benchmarking indicators in respect of the process benchmarking, performance benchmarking and strategic benchmarking. There will be enhancement to strive for innovative excellence and breakthrough thinking. To illustrate breakthrough thinking, very few SiMn/FeMn organisations are active participants in anthracite and coking coal mining. There is a need for a mindset shift, including considering offering better pricing for reductants. A mindset shift will result in a better understanding of the ferromanganese production by all roleplayers.

1.4 Justification of research
There have been fluctuations in the manganese ferroalloys market due to turbulences in the steel and iron ore commodity pricings. It then necessitates an insight into the technological processes used for ferromanganese production. The potentiality exists to examine shared applications like the furnaces, energy requirements, better materials handling techniques, mobility of labour, monitoring procedures, and research initiatives (Jones, 1994).

Benchmarking is a process of improving performance by continuously identifying, understanding, and adapting outstanding practices and processes found inside and outside the production facility. It is usually treated as a structural process. Developing a step-by-step model best provides the organisational and operational structure for benchmarking. Any type of benchmarking process model should provide an adequate framework for the successful planning and execution of a benchmarking exercise. It should be flexible enough to encourage the ferromanganese operation to modify the process to suit its needs and project requirements (Dattakumar and Jagadeesh, 2003).

Managers of FeMn/SiMn operations are continuously on the lookout for new technologies to enable quality improvements. Benchmarking is one such technique that has become popular in the recent times. Though benchmarking is not new, it has
now found more subscribers, and occupies a prominent place, helping quality upgradation. There are different types of benchmarking – and not all would be relevant to a metallurgical production environment. But there is always an opportunity to also derive useful benchmarking inferences from other best practices outside the metallurgical industry.

Benchmarking would not just be about making changes and improvements for the sake of it, but it is about adding value to a FeMn/SiMn production environment. No FeMn/SiMn production process should make changes if the changes are not going to be beneficial. When using benchmarking techniques, a furnace operation must look at how processes in the value chain are performed (Sweeney, 1994):

a. Identifying a critical process or sub-process that needs improvement
b. Identify a productive unit that excels in the process, preferably the best.
c. Contact the excelling unit and/or organisation that you are benchmarking for a visit to study the process or activity.
d. Analysing the data.
e. Improve the critical process at the operation.

Figure 1.4: High Carbon Ferromanganese production processes (courtesy of Gulf Minerals)
All of these factors lead to successful benchmarking of a manganese ferroalloy production process, or an area within a furnace operation. The main goals of efficiently producing FeMn are (Jones, 1994):

- To operate on a stable and high load;
- To minimise energy consumption;
- To take care of produced metal for high Mn yield; and
- To minimise emissions of CO₂ and noxious compounds and gases.

1.5 Scope of research
The scope of the study will focus on covering the process variables of the identified ferromanganese (FeMn/SiMn) smelting plants, including the efficiencies associated with them.

1.6 Conclusion
The following is how the study would be structured to follow the above stated research objectives:

*Chapter 1: Background*
In this first chapter, an attempt was made to introduce and analyse the topic. From an understanding of the topic, the rationale of the study was elaborated upon. And from the rationale of the study, the research problem and research question was introduced in detail. Flowing from the research question, were the objectives of the study. The study also introduced the research rationale that articulates the relevance of Benchmarking Techniques in the Production of Ferromanganese.

*Chapter 2: Ferromanganese Benchmarking Process*
The study would look at all or most of the available literature as in books and articles that are relevant for the study. These would be part of the primary sources of information. The fields that would be broadly looked at are: technology management, innovation management, strategic management of technology, engineering management, and marketing studies.
Chapter 3: Research Methodology
The third chapter would elaborate on the research process and how the research questions are being addressed. This will be a qualitative study based on the grounded theory and deductive analysis. Reliance would be highly placed on observations made from the plant facilities being visited. Importantly, the study would introduce a research design that would explain the identified aspects and variables of the ferromanganese benchmarking study. All or most of the data to be used would be declared, and guidance would be given about their relevance. Furthermore the limitations would be explained so that there would be clarity on the research tolerances accommodated in the study.

Chapter 4: Benchmarking Techniques in SiMn/FeMn Processes
The fourth chapter would elucidate the critical findings obtained from the ferromanganese production benchmarking study. All the findings should correspond to the research questions in Chapter 1 and the objectives advanced.

Chapter 5: Yield of Mn Ferroalloys Benchmarking
The fifth chapter would analyse the findings and develop a framework for their relevance in the current understanding and thinking of the production of ferromanganese in South Africa. There would be confirmation of known facts and possibly divergence of previously unknown facts in the field of pyrometallurgy. It would be relevant to also refer at this point to other fields of study like management sciences and innovation management to arrive at a wholistic understanding on how to improve the production of ferromanganese in South Africa.
Chapter 2
Ferromanganese Benchmarking Process

2.1 Benchmarking

2.1.1 Basics of Benchmarking

The organisational practice of benchmarking was pioneered by Xerox through the reverse engineering of products from other industry players in the copiers market in the late 1970s. In our context, benchmarking is performed by ferromanganese organisations to improve performance over time. It is broadly regarded as a process of identifying, understanding, and adapting outstanding practices from any organisation to help another organisation improve its performance and outcomes. Up to the year 2000, there were about 480 academic articles focusing on benchmarking (Dattakumar and Jagadeesh, 2003). And it is regarded as the practice of being humble enough to admit that another organisation somewhere is better at something, and being wise enough to learn how to match or even surpass them at it. But the performance and outcomes have to be informed by the SiMn/FeMn production process in this study. The general motto followed is as follows: Average is the bottom of good and the top of bad (Dattakumar and Jagadeesh, 2003; Jetmarova, 2011).

Summarily it could be said that benchmarking is a systematic and disciplined process of examining your own processes in the following manner:

(a) Finding who is better or best;
(b) Learning how they do it;
(c) Adapting it to your organisation;
(d) Implementing it; and
(e) Doing it continuously.

In the same vein, benchmarking is not:

(a) Only competitive analysis and benchmark cataloguing;
(b) Number crunching;
(c) Site briefings and observations;
(d) Just copying or catching up
(e) Spying
(f) Quick and easy.
2.1.2 Production Metrics

Due to the rapid growth in its steel production, China has become the most important market for manganese. To date, it has imported manganese ore rather than alloys, mostly from South Africa. It remains a sizeable exporter of manganese alloys, although the government is discouraging conversion agreements for reasons of environmental protection. The Nikopol plant in Ukraine is an important factor in the world market due to its sizeable capacity of 1.3m tonnes of FeMn/SiMn per annum (tpa). In 2005-2006, the government attempted to re-nationalize the plant. A dispute between the majority owner Interpipe and the minority shareholder Private Intertrading disrupted production over the past few years, and played a role in the tight market (Jones, 2007; Olsen et al, 2007).

Much of the production capacity in mainland Europe has closed over the past two decades, with Eramet’s Boulogne plant closing in 2003. In Norway, the manganese alloy plants are increasingly focusing on special grades. A limited number of global mineral resource groups continue their hold on high-grade manganese ore reserves, though in South Africa black-economic-empowerment initiatives may lead to new market entrants in the next few years. It is noticeable that the Mn ore producers have generally been reluctant to invest in manganese alloys capacity over the past decade or so because of the low-grade ore and the commodity price fluctuations (Jones, 2007).

The basic assumption is that it is the objective of ferromanganese producers to maximise the profit. The gain or profit is calculated as being the difference between the value of the produced products (the product value) and the value of the factors of production or costs used. This objective is often called simply profit maximisation. Based on the assumption of profit maximisation, three classical economic issues related to the act of producing can be identified (Olsen et al, 2007; Rasmussen, 2013):

(a) What to produce?
The producer usually has the option of producing alternative products with the available production plant. The producer may choose to produce one product e.g. the standard product which is the high-carbon ferromanganese (HCFeMn); or may produce a combination of HCFeMn, silicomanganese (SiMn), low-carbon ferromanganese (LCFeMn) and/or medium-carbon ferromanganese (MCFeMn).
(b) How much to produce?
A production process can be carried out more or less intensively. Products can be
grown using a larger or smaller amount of input materials. The size of the production
will depend on this. But what is optimal? To add more inputs like Mn ore, fluxes and
reductants, which would result in a large production, or to add less, which would
result in reduced costs?

(c) How to produce?
A product can often be produced in several ways. For example, it is possible to fight
undesirable elements by introducing certain fluxes or optimal tapping methods can
be used, or appropriate cooling methods should also be considered for better
crushing and screening of ferromanganese. But what choice would be optimal? What
kind of input would result in the lowest costs? Time is also an important factor. How
will the blending of the Mn ores and reductants be done to improve the kinetics of the
Mn ore reduction to achieve the required optimal results.

In general when speaking of production and related economic issues it is often
assumed that the ferromanganese production plant itself is a given. If this was the
case, the key economic issues concerning production would be related to the
question of how to best utilise the given production plant. Should the process
engineer use the blended or unblended Mn ore with which combination of reductants
and fluxes?

In practice the production metrics and economic issues concerning production are
not that well-defined. It is of course possible to make changes to the given production
plant, either by investing in new production facilities, or by renting or leasing some
aspects of the production facilities. The functional areas of managing the waste
materials could be viewed along the same lines as other factors of production, and
the issue of how much waste management efforts it would be optimal to apply, is in
principle also an entirely ordinary production metrics and an economic issue. Whilst it
is possible to be considerate of this important in principle, when it comes to decisions
which have long term implications and concern the production framework, such
issues are traditionally discussed within the discipline of investment and financial
planning.

There is no clear-cut distinction on how and when in the theory of production does
the fixed asset and the related fixed costs become variable. A description of the
theory of optimisation of production is based on the assumption that the price of
inputs and outputs are determined by external factors and cannot be influenced by the producer. And the SiMn/FeMn producer would be regarded as a price taker in this context. However, a generalisation of the theory to account for conditions in which prices are not constant but dependent on the size of the production could be worked out. Generally, there are no real problems in deriving principles for the optimisation under conditions in which prices are not fixed, i.e. they depend on the quantity produced. However, in this context, the problem of the pricing of output becomes an important subject (Jetmarova, 2011; Rasmussen, 2013).

2.2 Manganese Ferroalloy Production

2.2.1 Historical Overview

The history of ferroalloys is relatively short compared to bronze or iron development. Ancient iron artifacts investigated are mostly fairly pure iron, containing carbon as the only alloying element. Carbon control by carburising/decarburising treatments was traditionally understood by blacksmiths and was used throughout the “Iron Age” to adjust steel properties. Steel produced via the direct reduction route in bloomeries remained naturally unalloyed because iron oxide was reduced at such low temperatures that iron was formed in the solid state. Other components like manganese and silicon, which are typical in modern steels, were found only as natural impurities, yet mainly in slag inclusions in steel. When higher shaft furnaces were developed from bloomeries, stronger air blasting through tuyeres was needed. Temperature in the combustion zones was increased, and the iron formed dissolved more carbon and melted: thus, a blast furnace process was discovered. This development happened in the late Medieval Age in Central Europe (Tylecote, 1984).

The product was carbon-saturated cast iron that typically contained a small percentage of silicon and eventually also some manganese, depending on the ore composition. Pig iron from blast furnaces was used as foundry iron for castings or converted to steel by difficult and time consuming refining process. These processes were gradually developed, but steel from bloomeries kept its dominance until the 19th century. In the early 19th century, two main methods were used to refine hot metal from blast furnaces to steel. They were puddling with an oxidizing flame in a reverberatory furnace and the crucible process in which iron oxide (ore, scale) was added into hot metal to react with carbon and to get low-carbon steel (Nel, 1929; De Villiers, 1960; Roy, 1981; Tylecote, 1984; DeYoung, 1984; Steenkamp, 2012).
Highlights in the history of ferro alloy production in South Africa can be summarised as follows (Steenkamp, 2012):

(a) In 1918 Rand Carbide Limited was founded in Germiston, Transvaal for the production of calcium carbide and FeSi. The plant was relocated to Witbank in 1926, and in 1978 Highveld Steel & Vanadium Corporation Limited acquired the total issued share capital.

(b) In 1957 Assmang established the Cato Ridge Works (formerly Feralloys Limited) for ferromanganese production.

(c) Vanadium production started in 1957 in South Africa when Minerals Engineering of Colorado started producing vanadium pentoxide near Witbank, Transvaal. Anglo American acquired a majority share in 1959.

(d) Ferrometals became part of Amcor Ltd on 1 December 1959 when it purchased the entire share capital of Ferrometals Ltd from Wire Industries Steel Products and Engineering Company Ltd. At the time, Ferrometals had two 7 500 kVA furnaces for FeSi production on a 950-acre site near Witbank.

(e) Transalloys was started in 1960 in Witbank as an integrated HCFeCr/LCFeCr plant, based on the Perrin process. During 1967, the plant was converted from ferrochromium to ferromanganese production. At the time Airco Alloys had a 40% share in the plant, the balance belonging to Anglo American. In 1976, Highveld Steel acquired the 65% stake in Transalloys, previously held by Anglo American.

(f) The origins of Middelburg Ferrochrome now part of Samancor Chrome can be traced back to the RBM Alloys Ferrochrome Pilot Project in 1963.

(g) Palmiet Chrome Corporation came about through the endeavours of John Hahn. The first furnace for the production of charge chrome (ChCr) was started up on 22 February 1963 at the plant near Krugersdorp. On 28 December 1983 the first DC plasma arc furnace for ferrochromium production was commissioned at Palmiet.

(h) In 1971 Feralloys Limited erected a ferrochromium smelter at Machadodorp for the production of ChCr and LCFeCr.

(i) Amcor and S.A. Manganese merged in 1975 to become Samancor Limited.

(j) The CMI plant of JCI at Lydenburg (which was part of Xstrata) came into being during 1975 for the production of ChCr, based on the Showa Denko SRC process.

(k) Tubatse Ferrochrome was initially built as a three-furnace operation in 1975 as a joint venture between Gencor Limited and Union Carbide Incorporated of the
USA. In the same year, the Union Carbide Inc. shareholding was taken over by Samancor, and in 1989 Samancor acquired the Gencor Limited shareholding. During the years 1989-1990 the plant was expanded to five furnaces with the sixth furnace being built in 1996. The plant is situated in Steelpoort, Mpumalanga.

(l) Chromecorp Technology (Pty) Limited was registered in October 1987 and erected a furnace at Batlhako and later two furnaces for ChCr production in Rustenburg. In April 1995 the name was changed to Chromecorp Holdings Limited and the company was listed on the Johannesburg Stock Exchange on 23 May 1995. The company was delisted on 2 April 1998 and the full share capital was acquired by Sudelectra South African Holdings (Pty) Limited. The name Sudelectra SA was changed to Xstrata South Africa (Pty) Ltd on 9 April 1999. Xstrata became then the largest producer of ChCr in the world with plants at Rustenburg, Wonderkop, Boshoek, Lydenburg and the new plant near Steelpoort, Lion Ferrochrome.

(m) Hernic Ferrochrome was founded in 1995 for the production of ChCr, as a venture amongst Hernic (Pty) Ltd, ELG Haniel, Nippon Steel Trading and management. In 1996 the company commenced production on two 37MVA furnaces. Presently Mitsubishi Corporation holds the majority share of 53.2%.

(n) Purity Ferrochrome was started in Rustenburg in 1991 with two furnaces for ChCr production. It was taken over by CMI in 1993 and CMI in turn was taken over by Xstrata in 1998.

(o) ASA Metals (Pty) Ltd was established in February 1997 near Polokwane and is a 60/40 joint venture between EAMI (Eastern Asia Metals Investment Co. Ltd) and LEE (Limpopo Economic Enterprise). ASA Metals produces ChCr.

(p) South African Chrome & Alloys Limited (“SA Chrome”) was incorporated in South Africa on 24 July 1987 as Southern Witwatersrand Exploration Company Limited and changed its name to SA Chrome in December 1999. The main focus of the business is the ChCr smelter constructed at Boshoek. Subsequently, SA Chrome entered into a Pooling and Sharing venture with Xstrata in 2004.

Therefore from very small beginnings in 1918, the South African ferroalloy industry has prospered and grown to become a leading producer of bulk ferroalloys on a global scale, including ferromanganese.
2.2.2 Production Process

Manganese is almost always added to steel in the form of a manganese alloy. Mn ferroalloys are produced by smelting manganese ore predominantly in an electric-arc furnace, together with a carbon reductant, usually metallurgical coal. The smelting process removes most of the impurities from the manganese ore, so that the resulting manganese alloy product can be added to steel without re-contaminating the steel. Figure 2.1 below illustrates the furnace setting of where the smelting process occurs.

Smelting in an electric arc furnace is accomplished by conversion of electrical energy to heat. An alternating current applied to the electrodes causes current to flow through the charge between the electrode tips. This provides a reaction zone at temperatures up to 1700°C. The tip of each electrode changes polarity continuously as the alternating current flows between the tips. To maintain a uniform electric load, electrode depth is continuously varied automatically by mechanical or hydraulic means (Olsen et al, 2007).

The smelting process broadly consists of the following functional components (Figure 2.4):

(a) Materials receiving: raw materials shown primarily as charge feed;
(b) Production: processed material shown the recovered metal – HCFeMn, MCFeMn, LCFeMn and SiMn;
(c) Waste materials: waste materials would comprise of slag, baghouse dust, and slimes from candy filter; and
(d) Recovery: recycling for further processing like metal to crushing, slag for Mn reprocessing, and dust from baghouse with high Mn content; and
(e) Final processing: sale and disposal of SiMn/FeMn to market, aggregate from Metal Recovery Plant (MRP) to construction industry, slimes to dams, dust to dust storage, and waste slag to dump.

The thermodynamics for the production of manganese ferroalloys is widely known under different conditions because a general database has been developed to understand the relevant phases (Olsen et al, 2007; Tangstad, 2013). The challenge is generally the adaptation to physic-chemical conditioning which determine the kinetics of Mn metal recovery.
Manganese ores generally undergo the following phases under air:

\[
\begin{align*}
\text{MnO}_2 & \quad 500^\circ\text{C} \\
\text{Mn}_2\text{O}_3 & \quad 900^\circ\text{C} \\
\text{Mn}_3\text{O}_4 & \quad 1700^\circ\text{C} \\
\text{MnO} & \quad 1700^\circ\text{C} \\
\text{Mn} & \\
\end{align*}
\]

And the different Mn ore transformations have the following stoichiometric reactions in detail:

1. \(2\text{MnO}_2 + \text{CO}(g) \rightarrow \text{Mn}_2\text{O}_3 + \text{CO}_2(g)\) \(\Delta H^{298}_{298}=99.9\text{kJ}\)

2. \(3\text{Mn}_2\text{O}_3 + \text{CO}(g) \rightarrow 2\text{Mn}_3\text{O}_4 + \text{CO}_2(g)\) \(\Delta H^{298}_{298}=31.3\text{kJ}\)

3. \(\text{Mn}_3\text{O}_4 + \text{CO}(g) \rightarrow 3\text{MnO} + \text{CO}_2(g)\) \(\Delta H^{298}_{298}=16.9\text{kJ}\)

4. \(\text{MnO} + \text{C}(s) \rightarrow \text{Mn}(s) + \text{CO}(g)\) \(\Delta H^{298}_{298}=246.8\text{kJ}\)

The above reactions (1) – (3) are kinetically controlled for an optimal outcome of producing FeMn/SiMn. Figure 2.2 below further depicts a typical plant layout for the production of ferromanganese alloys as described by the various functional
areas of production. Beyond the normal production, there is sometimes a need to have a further metal recovery plant (MRP) to reprocess the slag.

Gas reductions of the higher Mn-oxides are exothermic reactions, and a considerable amount of heat is produced, thereby preheating the charge materials in the furnace. The extent of gas reduction is reflected by the furnace off-gas CO₂/CO ratio. Solid Mn₃O₄ converts easily to MnO in presence of CO according to reaction (3). The equilibrium CO/CO₂-ratio is 8 x 10⁻⁵ at 1000°C. The CO-gas reduction of Mn₃O₄ is thus a question of kinetics rather than thermodynamics. After the temperature has increased to about 1000°C the reaction on the coke surface is sufficiently rapid to make the ore reduction (3) and the Boudouard reaction (4) to run simultaneously. Thus, CO₂ formed by the reduction of Mn₃O₄ may react with carbon to give the overall endothermic reaction (5) below:

\[
(5) \quad \text{Mn}_3\text{O}_4 + 4\text{C}(s) \rightarrow 3\text{Mn} + 4\text{CO}(g) \quad \Delta H_{298} = +40.5\text{kJ}
\]

Figure 2.4: Typical plant layout for FeMn production

Manganese alloys generally have manganese content between 60% and 90%, with most of the remaining content being made up of iron and/or silicon. There are three main families of manganese alloys – silicomanganese, high-carbon ferromanganese and medium/low-carbon ferromanganese as illustrated in Table 2.1.
Table 2.1: Typical manganese ferroalloys and their compositions

<table>
<thead>
<tr>
<th>Alloy</th>
<th>%Mn</th>
<th>%Si</th>
<th>%Fe</th>
<th>%C</th>
<th>%P</th>
<th>%Necessary</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiMn</td>
<td>60-68</td>
<td>16-19</td>
<td>13-20</td>
<td>2.0</td>
<td>&lt;0.20</td>
<td>61</td>
</tr>
<tr>
<td>HCFeMn</td>
<td>65-80</td>
<td>1.0</td>
<td>10-25</td>
<td>7.5</td>
<td>&lt;0.35</td>
<td>28</td>
</tr>
<tr>
<td>LC/MCFeMn</td>
<td>75-90</td>
<td>&lt;1.0</td>
<td>2-12</td>
<td>&lt;1.5</td>
<td>&lt;0.30</td>
<td>11</td>
</tr>
</tbody>
</table>

The highest quality specialised steels generally use medium and low-carbon ferromanganese. Prices for medium-carbon ferromanganese are around 30-40% higher than prices for silicomanganese or high carbon ferromanganese. Global alloy production for 2013 was 17.4 million tonnes and is projected to increase by 40% over the next decade along with the increase in steel production.

2.3 Critical Processes

2.3.1 Definition of Processes

(a) Pre-reduction zone:
Reactions (1) – (3) above happen at the pre-reduction zone. These are reactions that prove to be on the critical path of whether there will be optimal Mn metal recovery or not. The processes have been proven to be kinetically dependent, and hence the physico-chemical conditions of the production process are important. These physico-chemical conditions could be the following: mechanical strength of the Mn ore, the grade of Mn ore, and the type of reductant used. There is proof that the strength and grade characteristics of Mn ore are usually inversely proportional. The Comilog ore of high-grade pyrolusite (MnO₂) in Gabon is a good example in this regard (Olsen et al, 2007; Steenkamp, 2012; Tangstad, 2013).

(b) Reduction/Cokebed zone
Reaction (4) occurs at the cokebed zone whereby MnO is reduced to Mn metal at the slag metal interface. This is a thermodynamically controlled reaction and could be controlled through various means like the preparation and testing of reductant material. Carbon as a reductant, additive or filler is an essential element in the processing of metallic ores and the manufacture of iron and steel in the metallurgical industry. In most cases, the element carbon is derived from coal and its carbon derivatives.
Coke is added as a source of carbon for Mn ore reduction. The interior of a furnace producing high carbon ferromanganese consists of two main zones with different characteristics: the low temperature pre-reduction zone, and the high temperature coke bed zone. As the raw materials move down in the pre-reduction zone, the higher oxides of manganese are pre-reduced in solid state to Mn$_3$O$_4$ and preferably further to MnO by CO gas formed in the crater zone. The extent of the simultaneously running Boudouard reaction ($\text{CO}_2$+C = 2CO) is responsible for the variation in carbon. After further reheating, the pre-reduced ore and added fluxes start melting at temperatures of about 1250°C to 1300°C.

The coke remains solid, so below this area there is a permanent coke bed. In addition, the melting together of ores and fluxes and reduction of MnO dissolved in the slag phase take place in the coke bed. The coke bed starts approximately at the tip of the submerged electrodes. It constitutes a permanent reservoir of coke. The relative amount of coke in the charge mix determines whether the coke bed increases, decreases or stable in size. In addition to being the chemical reductant it is also the heating element of the process where the electric current runs and ohmic energy is produced. The coke consumption ranges between 400 - 550 kg/ton HCFeMn, averaging 462 kg/ton. The coke consumption increases as the Mn ore blend weight increases, and Mn/Fe of the Mn ore blend decreases (Falcon, Du Cann, Comins, Erasmus, Den Hoed and Luckos, 2004; Eissa, El-Faramawy, Ahmed, Nabil and Halfa, 2012).

The properties of carbon required for the different processes in each metallurgical sector vary significantly and, for this reason, matching the correct carbon product to each specific process has become an important if not vital function in all sectors of the metallurgical industry. Such properties include softening, swelling, fusion and porosity in coke and char making, reactivity or carbon consumption of the carbon reductants for use in various processes using solid, gaseous and molten media, strength related to overburden pressure in blast furnaces, heat production during pre-reduction in pre-reduction kilns and in the Corex process, electrical resistivity related to degrees of graphitisation under various electric arc furnace conditions, and yet other related factors relevant in carbon fillers used in the manufacture of electrodes for electric arc furnaces (Fettweis, 1979; Falcon et al, 2004; Olsen, 2007).
It is known that there are limited sources of reductants with compositions that could be prepared through the advanced processing plants with modern designs. The various occurrences and qualities of coal are widely known and their petrographical characteristics could be verified and correlated for the most optimal thermodynamic conditions for manganese ferroalloys production (Fettweis, 1979; South African Coal Processing Society, 2012). Table 2.2 indicates the best known anthracite product specification in southern Africa, used as part of the feedstock by various ferroalloy production plants in South Africa:

Table 2.2: Best anthracite product specifications in Southern Africa

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>SIZE</th>
<th>H₂O%</th>
<th>Ash%</th>
<th>Vol%</th>
<th>FC%</th>
<th>T.S%</th>
<th>P₂O₅%</th>
<th>CaO%</th>
<th>GCV MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUFF</td>
<td>0.5- 10mm</td>
<td>1.4</td>
<td>9.0</td>
<td>5.7</td>
<td>84.4</td>
<td>0.68</td>
<td>0.005</td>
<td>0.28</td>
<td>32.0</td>
</tr>
<tr>
<td>BREEZE</td>
<td>0.5-15mm</td>
<td>1.2</td>
<td>11</td>
<td>5.5</td>
<td>82.4</td>
<td>0.72</td>
<td>0.007</td>
<td>0.34</td>
<td>31.2</td>
</tr>
<tr>
<td>PEAS</td>
<td>15-35mm</td>
<td>1.0</td>
<td>14</td>
<td>5.5</td>
<td>83.8</td>
<td>0.72</td>
<td>0.007</td>
<td>0.32</td>
<td>31.4</td>
</tr>
<tr>
<td>SPIRAL</td>
<td>0.5-2mm</td>
<td>2.5</td>
<td>14</td>
<td>5.7</td>
<td>79.1</td>
<td>0.74</td>
<td>0.008</td>
<td>-1.24</td>
<td>29.9</td>
</tr>
<tr>
<td>S/PEAS</td>
<td>15-35mm</td>
<td>1.0</td>
<td>9.0</td>
<td>5</td>
<td>85</td>
<td>0.70</td>
<td>0.007</td>
<td>0.32</td>
<td>32.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>P₂O₅</th>
<th>CaO</th>
<th>MgO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>SO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUFF</td>
<td>53.5</td>
<td>30.7</td>
<td>3.85</td>
<td>0.14</td>
<td>2.77</td>
<td>1.32</td>
<td>3.49</td>
<td>1.49</td>
<td>1.69</td>
</tr>
<tr>
<td>BREEZE</td>
<td>53.7</td>
<td>28.9</td>
<td>6.39</td>
<td>0.10</td>
<td>2.85</td>
<td>1.29</td>
<td>3.60</td>
<td>1.24</td>
<td>1.32</td>
</tr>
<tr>
<td>PEAS</td>
<td>53.0</td>
<td>31.4</td>
<td>3.88</td>
<td>0.14</td>
<td>3.00</td>
<td>1.35</td>
<td>3.63</td>
<td>1.58</td>
<td>1.33</td>
</tr>
</tbody>
</table>

(c) Fluxes

Limestone and dolomite are used as flux materials. These basic fluxes are added to give the slag suitable chemical properties, smelting temperature and viscosity in order to secure good furnace operation and a high manganese recovery. The amount of added limestone and dolomite depends on the required CaO and MgO to attain the specific slag basicity.

The flux consumption per tonne HC FeMn ranges between 200 and 450 kg, average 340 kg. About two third of this amount is dolomite and the other third is limestone. The flux consumption is correlated with the basicity and SiO₂ content of Mn-blend. As the silica amount or percent in Mn-blend increase, the flux addition increases. On the
other hand, as the basicity of Mn-blend increases, the flux addition decreases (Eissa et al, 2012).

(d) **Electrodes**
The electrodes of the three-phase electric furnace are made of carbonaceous material, and they consumed during normal production. The consumption is usually large near the tip of the electrode where the temperature is high and the reactants are more active. To keep the electrode tip at the same position it is therefore necessary to prolong the electrode regularly. The electrodes consumption per ton HCFeMn ranges between 8 and 37 kg (average 17.5 kg).

The electrodes consumption increases as the coke consumption per ton HCFeMn increases. Electrodes’ casings are composed of low carbon steel and are consumed with the consumption of electrodes. The electrodes casing consumption ranges between 0.4 and 1.3 kg/ton HCFeMn, average 0.6 kg/ton (Eissa et al, 2012).

### 2.3.2 Input materials preparation

#### 2.3.2.1 Known economical deposits
The choice and preparation of Mn ore is critical to the process of ferromanganese production. It was determined that three types of Mn deposits have produced the great bulk of the high quality Mn ores used in the ferromanganese production industry. The deposits are as follows: manganese carbonate deposits from Ghana, Congo Guyana and Burkina Faso; manganiferrous silicate carbonate beds from Brazil and South Africa; manganese-rich beds deposited at the margins of epicontinental basins of Gabon, Brazil, Georgia and Ukraine. Changing circumstances and declining prices have discouraged the exploitation of new deposits (Roy, 1981; Machamer, 2002).

In general, the world's largest Mn deposits are found in seabed of oceans. These Mn deposits have the compositions of ferromanganese. They are either found as nodules or crusts, and usually develop into noticeable structures through accretion. The existence of these deposits is influenced by sedimentary processes through precipitation between different phases of the host environment. And another process that has been suggested is caused anomalous seafloor heat fluxes with potentially the hydrothermal brines being the secondary source of precipitated marine ferromanganese (Halbach et al, 1988; Baturin, 1988).
Here are some of the known significant Mn ores (Roy, 1981; Tangstad, 2013):

Table 2.3: Most known Mn minerals

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical Formula</th>
<th>Mn content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oxide Types</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrolusite</td>
<td>MnO₂</td>
<td>63.2</td>
</tr>
<tr>
<td>Vernadite</td>
<td>MnO₂.H₂O</td>
<td>44-52</td>
</tr>
<tr>
<td>Braunite</td>
<td>3(Mn,Fe)₂O₃.CaSiO₃</td>
<td>48.9-56.1</td>
</tr>
<tr>
<td>Braunite II</td>
<td>7(Mn,Fe)₂O₅.CaSiO₃</td>
<td>52.6</td>
</tr>
<tr>
<td>Manganite</td>
<td>γ-MnOOH</td>
<td>62.5</td>
</tr>
<tr>
<td>Hausmannite</td>
<td>(Mn,Fe)₃O₄</td>
<td>64.0</td>
</tr>
<tr>
<td>Bixbyite</td>
<td>(Mn,Fe)₂O₃</td>
<td>55.6</td>
</tr>
<tr>
<td>Cryptomelane</td>
<td>(K,Ba)Mn₁₆O₁₆.xH₂O</td>
<td>55.8-56.8</td>
</tr>
<tr>
<td><strong>Carbonate Types</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhodochrosite</td>
<td>MnCO₃</td>
<td>47.6</td>
</tr>
<tr>
<td><strong>Silicate Types</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhodonite</td>
<td>MnSiO₃</td>
<td>42.0</td>
</tr>
<tr>
<td>Tephroite</td>
<td>Mn₂SiO₄</td>
<td>54.4</td>
</tr>
<tr>
<td><strong>Sulphide Types</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alabandine</td>
<td>MnS</td>
<td>63.2</td>
</tr>
<tr>
<td>Gauerite</td>
<td>MnS₂</td>
<td>46.2</td>
</tr>
</tbody>
</table>

2.3.2.2 Observed Mn ore handling

For one ferromanganese plant in Egypt that is composed of blends of local manganese ores and imported manganese sinter, is used for producing the high-carbon ferromanganese. The local manganese ores are low and medium grades with Mn/Fe ratio ranges between 3.0 and 5.5. Manganese to iron ratio is very important in the ferromanganese production process. Mn/Fe weight ratio of 7.5 is required for production of standard ferromanganese alloy with 78% Mn. Furthermore, the local manganese ores vary widely in their content of manganese, iron, silicon, alumina, lime, magnesia, potassium and sodium oxides, barium oxide and phosphorus. Mixtures of two Mn ores are usually used to be blend with Mn sinter. The charged Mn ores mixture amounts to 890 - 1890 kg per tonne produced alloy, averaging 1375 kg/ton, with Mn/Fe ratio ranging between 3.3 and 5.5, average 4.08 (Eissa et al, 2012).
Again from previous studies, the impact of the rate governing parameters viz. decarburisation cycle period, temperature of decarburisation, particle size of the reactants and pressure on the extent of decarburization was studied. In general, maximum decarburisation could be noticed over the span of 2 to 5 hours with tolerance of ±0.5 hour, for a fixed set of parameters i.e. temperature, particle size. Decarburisation temperature should preferably be maintained around 1373 K for compensating the endothermic reaction heat. It will impart higher driving potential for completion of decarburisation reactions leading to about 60 per cent carbon removal (Bhonde, Angal, and Tupkary, 2007; Gasik and Jalkanen, 2013).

The decarburisation with particle size of high-carbon ferromanganese in the range 45mm to 53mm was comparatively found more effective than 90mm to 105mm. It can be attributed to the availability of larger quantum of reaction sites due to decrease in grain size of the reactants. Application of vacuum improved the efficiency of the process. Manganese enrichment up to ten weight percent (i.e. 82.5 weight per cent Mn in the final product), along with good decarburisation could be obtained by subjecting the reacting mass to the vacuum of the order of 0.001 torr (Bhonde, Angal, and Tupkary, 2007; Gasik and Jalkanen, 2013).

An attempt was made to understand the oxidation behavior of the high-carbon ferromanganese during solid-state decarburisation by externally supplied CO₂ by application of Wagner's oxidation model. Based upon the mass change results, the rate constant and activation energy values for the same were calculated which showed possibility of diffusion controlled mechanism at high temperature regime. The validity of application of the un-reacted core model was tried. For this the fractional conversion parameter values for different reaction control mechanisms were determined on the basis of carbon depletion data. The best fit was obtained for product diffusion controlled equation indicating it to be the probable rate-controlling step (Bhonde, Angal, and Tupkary, 2007; Gasik and Jalkanen, 2013).

### 2.4 Functional benchmarking and FeMn/SiMn production processes

#### 2.4.1 Interface of benchmarking and production

The interface of benchmarking and the ferromanganese production process has been clarified by the choice of unit of analysis i.e. the process of FeMn/SiMn production. It involves the following functional areas as described above: (a) Materials receiving: raw materials shown primarily as charge feed; (b) Production: processed material shown the recovered metal – HCFeMn, MCFeMn, LCFeMn and SiMn; (c) Waste
materials: waste materials would comprise of slag, baghouse dust, and slimes from candy filter; (d) Recovery: recycling for further processing like metal from crushing, slag for Mn reprocessing, and dust from baghouse with high Mn content; and (e) Final processing: sale and disposal of SiMn/FeMn to market, aggregate from Metal Recovery Plant (MRP) to construction industry, slimes to dams, dust to dust storage, and waste slag to dump (Olsen et al, 2007). From Figure 2.4, the following table can be formulated:

<table>
<thead>
<tr>
<th>MATERIALS RECEIVING</th>
<th>PRODUCTION OUTCOMES</th>
<th>WASTE MATERIALS</th>
<th>RECOVERY</th>
<th>FINAL PROCESSING</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAW MATERIALS</td>
<td>PROCESSED MATERIALS</td>
<td>PROCESSED WASTE</td>
<td>FURTHER PROCESSING</td>
<td>SALE AND DISPOSAL</td>
</tr>
<tr>
<td>Mn ore</td>
<td>HC FeMn</td>
<td>Slag</td>
<td>Recycling</td>
<td>Marketing</td>
</tr>
<tr>
<td>Coke</td>
<td>SiMn</td>
<td>Baghouse dust</td>
<td>crushed metal</td>
<td>Dust to dust storage</td>
</tr>
<tr>
<td>Fluxes</td>
<td>MC FeMn</td>
<td>Slimes</td>
<td>Slag reprocessing</td>
<td>Aggregate to other industries</td>
</tr>
<tr>
<td>Reductants</td>
<td>LC FeMn</td>
<td></td>
<td>Dust reprocessing</td>
<td>Slag to dams</td>
</tr>
</tbody>
</table>

Also as stated as above, the context has to be clarified: the Mn ore that is an input material was described as of the type manganiferrous silicate carbonates, and not the oxide type. Where there are oxide types, they are very marginal and are not economic for large-scale exploitation (Jones, 2007). The study should in essence explore how the easily accessible input materials can be utilised to make the production of manganese ferroalloys competitive in South Africa. A comparative advantage already exists due to South Africa having the largest reserves of Mn ore in the world, which are greatly attributed by the Kalahari manganese reserves (Steenkamp, 2012).

From Figure 2.3 below further simplifies the production process as tabulated in Table 2.2. Various functional and sub-functional ferromanganese plant areas should be able to uphold certain quality standards with respect to the required product specifications, materials handling, waste management, recycling procedures, and the final sales and disposal of the FeMn/SiMn products. The acceptable quality standards would also in turn create confidence from the product buyers. This would furthermore ensure that the ferromanganese production process contributes to the profitability of the organisation.
2.4.2 Characterisation of production focus areas

Functional benchmarking could be explored if it can develop relevant indicators for functional benchmarking given the identified SiMn/FeMn production functional areas. The benchmarking will be biased towards the physicochemical aspects like the functional areas described under Table 2.2 and Figure 2.3 above. The thermochemical data is taken as a constant since there is an established database, and associated phase diagrams have been developed by industrial producers of FeMn/SiMn (Olsen et al, 2007; Tangstad, 2013).

The other form of benchmarking that will be relevant for the study is generic benchmarking because FeMn/SiMn is part of a value chain in the steel making process. So the behaviour of the three-phase electric arc furnace also finds application in steel production and other ferroalloys like ferrochrome, ferrosilicon, ferrovanadium and ferronickel. There are elements that could be learnt from other ferroalloy producers on the efficiencies of production e.g. the usage of the same facilities for the production of ferromanganese and ferrochrome in South Africa.
2.5 Synthesis

It has been illustrated that ferromanganese production process would focus on the physico-chemical aspects of the production process. The physico-chemical conditions influence the kinetics of the Mn ore charge. From previous experimentation, the chemical transformations of Mn ores start at 1000°C, and hence the kinetic control of the system is critical to the eventual recovery of the Mn metal, as per reactions (1) – (3) in the reaction zones. It was also stated that the thermochemical database of the ferromanganese production processes is well documented and known, and phase diagrams could always be derived from any existing reaction conditions.

The physico-chemical aspects include the Mn ore composition and preparation, Mn ore mechanical strength, reductant composition and preparation, and the efficient usage of electricity amongst others. Such aspects would influence the reactivity of the Mn ore and the efficient fueling of the furnace system. Benchmarking should look at specific uncertainties in a ferromanganese process, and compare the practice in the industry in general. There will be specific focus on determining the critical indicators of functional benchmarking, with inferences from the generic benchmarking. Similar inferences could be made on the nature of management, particularly technological management of the ferromanganese production processes.
Chapter 3
Research Methodology

3.1 Research overview

3.1.2 Overview

The production of ferromanganese and its application is a function of the required FeMn/SiMn specifications by steel producers. Globally, the steel producers are involved in innovation activities at a level of markets and products on the one hand, and processes, on the other. In terms of markets and products, research and development is highly business-oriented, ensuring a shorter time-to-market and improved competitiveness, and covers the following sectors (AMSA, 2010):

- Automotive
- Packaging
- Construction
- General industry
- Long products
- Stainless steels
- Special plates

The preceding chapter was a review of literature relevant to this study of benchmarking techniques of ferromanganese production. This chapter will focus on the research methodology and design employed in this study. Admittedly, there is very little academic material on benchmarking of ferromanganese production techniques, particularly for a developing country environment such as South Africa (Sedumedi and Pan, 2014). The current limited scholarship all concur that the benchmarking exercise is a continuous improvement on product and/or production quality (Dattakumar and Jagadeesh, 2003). There are a large number of benchmarking models and orientation in them for pyrometallurgy is not easy. The research intends to propose best practices that could be implemented and those that have been observed (Jetmarova, 2011; Sedumedi and Pan, 2014).

This study will be informed by basing its observations and interactions with specific production facilities. Such production facilities would be informed by the production methodologies employed, and could be approached from two distinct dimensions or a combination thereof:
Benchmarking from a ferromanganese production survivalist perspective:
The leading producers of manganese ferroalloys are also owners or part owners of manganese mines. These producers could be having an inward perspective of what could influence their production parameters because the raw materials are of known properties. There has always been availability of good quality manganese ore in countries like South Africa, Gabon, Russia and Australia and Ghana. However, the ore resources would always deplete in terms of quality, and quantity in some instances, as a mining and geological reality. The comparative advantage is unnoticeably seen as the most critical factor of benchmarking by these producers.

Furthermore, for this study, the benchmarking indicators in respect of ferromanganese production performance are purely identified as being within the constraints of the organisation. Factors that would be considered here would be the following: reliability of Mn ore from own sources, carbon monoxide (CO) reactivity of Mn ore, enthalpy values for heating and reduction, reduction rate and liquidus of different slags, and carbon dioxide (CO$_2$) reactivity of carbon materials (Olsen et al, 2007).

Benchmarking from a ferromanganese production competitive perspective:
Ferromanganese producers could also seek learning experiences from other known good producers. It would be an identification of best practices within the sector. In this instance, for example, unknown properties of excellent raw materials could be a preserve of certain FeMn/ SiMn producers, bridging effect and permeability of various raw materials, and electrical conductivity of the cokebed surface. The raw materials include good quality reductant and Mn ore (Olsen et al, 2007).

It would be important to consider this benchmarking perspective because it introduces what is not known to a FeMn/SiMn facility. More will be understood about what differentiates one FeMn/SiMn facility from the other. Where appropriate, certain inferences would be made to identify the key indicators that define the benchmarking techniques.

3.2 Research design
3.2.1 Description of design
A research design has a point of departure – that being the research questions; hence, it focuses on the outcome of the study. Here focus is on the planning of the study and the kind of result being envisaged. The design must have some logic of arriving at the required evidence to address the research questions satisfactorily. It is
observed that both the primary question and any secondary question are exploratory and descriptive (Mouton, 2001; Yin, 2002). To review, the research question is as follows:

**What are the benchmarking techniques that can be used in the production of manganese ferroalloys, in this instance ferromanganese (FeMn) and Silicomanganese (SiMn)?**

The study would be a reflection on the practice of pyrometallurgy in the context of environments dominated by various organisations producing FeMn and SiMn. Other insights would be thrown into the picture to amplify the theoretical insights in assisting to have diverse constructs for theoretical robustness, e.g. ferrochrome and steel production processes and facilities, and broadly various insights within the ferroalloy production sector.

The study emanates from a critical industrial interest and would be a reflection on a particular aspect of SiMn/FeMn pyrometallurgical processes, i.e. general process practice within the producing organisations. It would be a qualitative study dominated by empirical research whereby analysis would be deductive, thematic and also based on the methodological approach. The SiMn/FeMn producing South African metallurgical plants will form the basis of the study as a key area of research focus. On cases for inference, lessons from other global SiMn/FeMn facilities will be studies and insights accumulated. The dominant research design classification would be empirical, mostly methodological based on numeric, textual, and hybrid data i.e. surveys, secondary data analysis, partly from experimentation done and comparative studies. In this instance, the research environment is of a high control (Mouton, 2001). Therefore, no theory or hypothesis would be formulated, and the study would be guided by certain theoretical framework expectations.

### 3.2.2 Design context

Modern FeMn/Si production processes are mature and known. The added element that needs to be observed is the creation of strongly innovative SiMn/FeMn pyrometallurgical processes which could be influenced by the following four trends: (1) innovation and influx of new technology, (2) pressure on time to market, (3) increasing customer demands, and (4) globalisation (Stehr, 2000; Brombacher, Sander, Sonnemans and Rouvroye, 2005). It was established that benchmarking was influenced more significantly by best practices controlling the strategic implementation of production processes (project selection, goals, technology
leadership, product strategy and customer involvement) than by metallurgical processes associated with the execution of benchmarking (process control, metrics, documentation and change control). Best practices associated with strategic implementation were widely adopted than best practices associated with controlling and executing benchmarking (Dooley, 2000). With that said, the aim of the research design would be to develop new methods in benchmarking the production of manganese ferroalloys, a form of key indicators as a test (Mouton, 2001).

The study does not have a serious issue with the conventional positivist paradigm because validity, reliability and objectivity are criteria used to evaluate the quality of the research. As the study follows an evaluative and descriptive method, qualitative analysis would be relevant from the positivist tradition in its fundamental assumptions, research purposes and inference processes, thus making the conventional criteria suitable for judging its research results (Bradley, 1993).

Possible limitations would be understood from the context of the methodological studies being largely context bound in the developed countries’ environment. Very little methodological research has been done in a developing-country environment. The limitations would thus how the data has to be sampled to be representative of the actual production phenomena. In such studies, data is collected through standard design types like surveys and experiments. For example, in our study we have the endothermic Bourdouard reaction i.e. \( \text{C(s) + CO}_2(g) \rightleftharpoons 2\text{CO(g)} \), which has well-known recorded variables like the enthalpy of the reaction at 172kJ.mol\(^{-1}\). Similarly, \( \text{C(s) + MnO(l) \rightleftharpoons Mn(l) + CO(g)} \), is a well-recorded exothermic reaction at the metal-slag interface. Therefore, any source of previous research error in the known analysis of the pre-reduction and cokebed zones could be a serious limitation of the methodological research.

![Figure 3.1: Ferromanganese furnace view](image)
3.3 Research process

3.3.1 Process context

The research process is a reference point for the whole methodology of research (Mouton and Muller, 1998). The research process would mostly be dominated by survey research, as the knowledge domain is currently limited with regard to the practice of benchmarking particularly when evaluating technological processes and products in a developing country environment. There would thus be heavy reliance on methodological research and secondary data analysis. The study was based on an approach to identify the key and/or representative production processes environments in South Africa as in the reference cases to be used.

Observations will be made and production processes physically surveyed. Secondary material will be collected and transformed into data categories for further analysis and evaluation. Hence, phenomenologically the results would be able to illuminate the specifics of various situations to arrive at a best method(s), which are representative of the SiMn/FeMn production processes. Accordingly, the study will attempt to develop methods through key indicators of how benchmarking can be developed and conducted in South Africa. Therefore, the types of evidence required to undertake the study would require surveys, observations, interviews, a collection of historical data for analysis, the observing and evaluating of the plant pyrometallurgical practices, the analysis of existing data, and in-depth literature review.

Analysis of data was undertaken by looking at the SiMn/FeMn production process as the unit of analysis. Existing data was analysed by doing comparative analysis and performing secondary data analysis of the identified primary and secondary text data. Some of the observations made during the course of the research process were substantiated by accurately recording each step along the way.

A fundamental part of the analysis method in methodological research is the inductive analysis adopted in this study through the evaluation and description of the identified plant production processes. The historical research errors of interviewer and observer effects could be unearthed by using both normal statistical and qualitative forms of data analysis in this methodological study (De Leeuw, 1992).
3.3.2 **Interpretive analysis: grounded theory**

Grounded theory has been around since 1967 after the groundbreaking study of Glaser and Strauss – mainly focusing on qualitative aspects of research. Qualitative content analysis goes beyond merely counting words or extracting objective content from texts to examine meanings, themes and patterns that may be manifest or latent in a particular text or processes. It allows a researcher to understand conceptual reality in a subjective but scientific manner (Glaser and Strauss, 1967).

Comparing qualitative content analysis with its rather familiar quantitative counterpart could enhance one’s understanding of the method and would be tried wherever possible, although maintaining the objectives of the study. First, the research areas from which they are developed are different. Quantitative content analysis is used widely in mass comparisons of phenomena as a way to count manifest conceptual elements, an aspect of this method that is often criticised for missing syntactical and semantic information embedded in the text (Glaser and Strauss, 1967). By contrast, qualitative content analysis was developed primarily in the non-exact sciences in order to explore the meanings underlying physical messages. Secondly, quantitative content analysis is deductive and potentially deterministic, intended to test hypotheses or address questions generated from theories or previous empirical research.

Qualitative content analysis is mainly inductive, grounding the examination of topics and themes, as well as the inferences drawn from them, in the data. In some cases, qualitative content analysis could generate theory. Thirdly, the data sampling techniques required by the two approaches are different. Quantitative content analysis requires that the data be selected using random sampling or other probabilistic approaches so as to ensure the validity of statistical inference (Eisenhardt and Graebener, 2007).

By contrast, samples for qualitative content analysis usually consist of purposively selected texts or process observations that can inform the research questions being investigated. This is illustrated by the selection of the texts in the literature review and reference cases. Last, but not least, the products of the two approaches are different. The quantitative approach produces numbers that can be manipulated with various statistical methods. By contrast, the qualitative approach usually produces descriptions or typologies, along with expressions from subjects reflecting how they view the non-exact world.
By this means, the perspectives of the practitioners of managing and operating the ferromanganese production processes can be better understood by the researcher as well as the users of the study’s results. Qualitative content analysis pays attention to unique themes that illustrate the range of the meanings of the phenomenon rather than only the statistical significance of the occurrence of particular texts or concepts (Glaser and Strauss, 1967; Eaves, 2001).

In discovering theory, one generates conceptual categories or their properties from evidence; then the evidence from which the category emerged is used to illustrate the concept. The evidence may not necessarily be accurate beyond doubt, but the concept is undoubtedly a relevant theoretical abstraction about what is going on in the area studied. Theoretical sampling simply means that cases are selected because they are particularly suitable for illuminating and extending relationships and logic among constructs (Eisenhardt and Graebener, 2007).

### 3.3.3 Process of benchmarking

The current study would primarily be a methodological study making use of methods of formulating information to be quantitative wherever possible. In this context, more clarity would be attained with the specific process aspects of the study and the identified unit of analysis. In addition, a better generalisation could be obtained as subjectivity could be minimised. The inductive study would be enhanced by reliable statistical data such that some deductive observations could be made. Hence, a qualitative-quantitative research design could be followed in an attempt to arrive at a theoretical model and generalisable results that identify the benchmarking indicators.

There is content analysis that is premised on grounded theory such that there is a strong intellectual justification for using qualitative research to develop a theoretical analysis (Glaser and Strauss, 1967). These studies suggest that the generalisation model represents a research approach that successfully accomplishes two goals. First, it provides significant insights into the research problem and thus responds to the many calls for discovery-orientated research. Secondly, it assures scientific rigour and allows deriving generalisable results from both quantitative and qualitative data. In a generalisation design study, qualitative material is inductively explored and then analysed. However, care would be taken for a theoretical framework to emerge and not be enforced.
Applying a systematic procedure, a new theory as well as a basis for quantitative analyses can be derived. The purpose of this methodological research is to develop a theoretical framework and not to test it. That being the case, theoretical sampling of multiple cases would be appropriate rather than undertaking representative sampling. This is done to extend relationships and logic amongst the various constructs. Representative sampling could be stratified and/or random (Glaser and Strauss, 1967).

Single-case research typically exploits opportunities to explore a significant phenomenon under rare or extreme circumstances. While single-case studies can richly describe the existence of a phenomenon, multiple-case studies typically provide a stronger base for theory building. Multiple cases, i.e. at least five, would be chosen to create a more robust theoretical framework because the propositions are more deeply grounded in varied empirical evidence i.e. pyrometallurgy and benchmarking.

It is easier to determine accurate definitions and appropriate levels of construct abstraction from multiple cases because constructs and relationships are more precisely delineated (Eisenhardt and Graebener, 2007). Hence, the steel-producing organisations and mining resources organisations would be investigated for this study, as will be inferences from other industrial sectors. An integrated design would be followed in a qualitative research design to arrive at a built theory. Its analysis would normally follow the following stages as research develops for a generalisation model (Eaves, 2001):

*Activity-by-activity analysis --- Brief Analytical Concepts --- Categories --- Sub-categories --- Linkages among Categories --- Core Theoretical Framework*

There would be memos recorded throughout the research process to capture characteristics, properties and dimensions from sub-categories. Also, there would be constant comparison to classify concepts into categories. Various phrases would be clustered and delineated to arrive at categories and mini-theories. Thus, the integration of the mini-theories would result in an inductively generalised framework, i.e. a theoretical or conceptual framework (Glaser and Strauss, 1967; Eaves, 2001).
3.3.4 Data gathering

There would be heavy reliance on empirical data although the non-empirical data would provide complementarity to have diverse contexts to arrive at useful constructs. The types of data that follow will be examined.

3.3.4.1 Empirical data

Here, cases would be divided into three primary and two secondary reference cases and various data would be consulted from various sources in the industry including suppliers of ferromanganese-producing equipments. The five reference cases are a HC FeMn producer, a SiMn producer, a LC/MC FeMn producer, a new HC FeMn producer, and a HCFeMn producer for the European market.

The semi-structured interviews would be carried out on the primary reference cases. In addition, the secondary data analysis (SDA) and questionnaires would be relied upon with the secondary/tertiary reference cases. Table 3.1 illustrates how the various data collection methods would be undertaken from the various reference cases. They are referred as reference cases to illustrate that the emergent theoretical framework would be dependent on theoretical sampling and that the ethnographic research based on semi-structured interviews and questionnaires would be complemented by content analysis of secondary data such as annual reports.

Table 3.1: 2 x Primary (P) and 3 x Secondary (S) Reference Cases

<table>
<thead>
<tr>
<th>Reference Cases</th>
<th>Mn ore type</th>
<th>Case Type</th>
<th>Context</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. P1: HC FeMn producer</td>
<td>Braunite II, Rhodochrosite and Hausmannite</td>
<td>Primary Observations SDA</td>
<td>Largest ferromanganese producer in SA</td>
</tr>
<tr>
<td>2. P2: SiMn producer</td>
<td>Braunite, Manganite and Hausmannite</td>
<td>Primary Observations SDA</td>
<td>7th largest SiMn producer in the world</td>
</tr>
<tr>
<td>3. S1: Refined LC and MC FeMn</td>
<td>Pyrolusite (MnO₂)</td>
<td>Secondary SDA Observation</td>
<td>Significant LC and MC FeMn producer</td>
</tr>
<tr>
<td>4. S2: HC FeMn producer</td>
<td>Pyrolusite (MnO₂)</td>
<td>Secondary SD</td>
<td>New entrant HC FeMn producer</td>
</tr>
<tr>
<td>5. S3: HC FeMn producer</td>
<td>Pyrolusite (MnO₂)</td>
<td>Tertiary SDA</td>
<td>Significant HC FeMn producer for the European market</td>
</tr>
</tbody>
</table>
The organisations in Table 3.1 above were chosen on the basis of their uniqueness in respect of the following factors: specific production processes, newness to the market, economic impact, global impact, and perceived business profitability. Important questions would need to be asked to achieve best practices in the production of FeMn/SiMn, even though it may not be possible to have all the answers (Maack, 1974; Narayanan, 2000). The process engineer would be requested to respond to the various aspects of the production process, and the background questions (1) to (8) that would be attempted for clarity by observations and requesting for clarity.

From best practice studies across various organisations and metallurgical industries, the onsite visit and observations would attempt to understand the reference cases. The standard background questions that influence decision-making in metallurgical organisations for the primary reference could be framed in the following manner (Cooper, 1993):

1. **Customer Requirements:** How potential customer requirements are identified, defined and changed.
2. **Product Strategy:** How benchmarking is aligned with internal constraints and with external factors such as the product marketing environment, regulations and competition.
3. **Concept Generation:** How candidate concepts for new products are generated or acquired.
4. **Concept Selection:** How candidate product concepts are screened and concepts selected for further development.
5. **Concept Design:** How the selected concept is designed at a high level.
6. **Detail Design and Redesign:** How product details, materials, and dimensions are specified.
7. **Manufacturing and Marketing Preparations:** How manufacturing processes are developed and channels to get the products to the customers are established.
8. **Product Improvement and Disposal:** How production processes’ shortcomings are identified, improvements made, and how products are disposed of at the end of their life cycle.
• **Secondary data analysis**
  This would entail the analysis of existing reports and data. The reports would include the organisational annual reports from the reference cases and published official reports.

• **Observation studies**
  A number of visits would be undertaken on a continuous basis to primarily P1 and P2. S1, S2 and S3 will be treated differently. This would include plants and facilities visits to observe how production, processes and services are implemented or installed or upgraded. The cases chosen were unique in the sense that they captured particulate production processes. And, additionally, the cases distinguish themselves as having a global profile in many respects.

• **Historical analysis**
  This would include research reports and historical organisational data as contained in the previous annual reports and organisational records.

3.3.4.2 **Non-empirical data**
  It can be noted that hybrid data would be used in doing the processes’ observation studies and analysis of existing metallurgical and benchmarking data.

• **Literature review**
  From Chapter 2, the literature reviewed covered the various experimental production processes of FeMn/SiMn, registered patents and the theory of benchmarking. It would offer useful insights to complement the variables.

There are two approaches that will be followed to design the benchmarking study such that it does not lose its scientific rigour:

(a) **Grounded theory approach**
  Grounded theory is a qualitative research method that was developed for the purpose of studying phenomena from the perspective of symbolic interactionism. Grounded theory uses a systematic set of data collection and analysis procedures to develop an inductively derived theory from the data. Field research, site visits and observations are the usual methods for gathering data (Glaser and Strauss, 1967).
The generation of the framework occurs during actual research and is based on comparative analyses between or among groups of pyrometallurgical processes within a particular area of interest i.e. ferromanganese production processes. This comparative analysis is a central feature of grounded theory and is often referred to as the constant comparative method (Glaser and Strauss, 1967). Therefore, the grounded theory method, along with its technique of constant comparison, allows a researcher to identify patterns and relationships between these patterns, particularly when looking at an external study field to pyrometallurgy i.e. Benchmarking.

(b) Methodological study

The methodology employed in this study is to develop a new method such as evaluation criteria and indicators. It will also be based on the analysis of the scientific method whereby the key research question is exploratory and evaluative. The research design is primarily based on positivist approaches rather than interpretive approaches. The grounded theory is an example of an interpretive approach. In pursuing this research as a scientific activity, the practice of pyrometallurgy as a science would need to be interrogated. An analysis of the production methods as second-order disciplines from benchmarking would be undertaken. The procedures and structures of the various FeMn/SiMn production methods or approaches would be the reference points of the study (Losee, 2001).

- Study design

Our design classification will be composed of both empirical, numerical and hybrid data. The control of data will be high because there are already established practices of conducting the production of ferroalloys. It will be clear that the application of the methodology followed is to develop new measuring instruments, tests and indicators. From this application premise, the mode of reasoning to be followed will be that of an inductive methodological study, analysing the empirical data such that there will be an exploratory factor analysis. The exploratory factor analysis would lead to the development of a factor structure even though there is no benchmarking theoretical model (Mouton, 2001).

Emphasis would be placed at the logic of scientific explanation where there would be scrutiny on the explanation of pyrometallurgical facts. The scrutiny would largely be an endeavour to understand how the various ferromanganese producers conduct and frame the processes of production. New types of interpretations would be sought such that precedents are not ignored in evaluating the current practices. Emergent
new practices could signal the existence of previously ignored production methods (De Solla Price, 1975). It was previously illustrated by Kuhn that some essence is lost when science is reconstructed in the categories of formal logic or normal science (Kuhn, 1962).

- Data collection method and analysis
The data collection method to be used would be probability sampling whereby reference cases will be identified as in section 3.4. Data collection would be done with surveys, experiments and comparative studies. It will also include secondary data analysis from the records of the companies being cased. Hence a content analysis of annual reports and business operation manuals would be reviewed to determine how the FeMn/SiMn production process is used to manage the efficiencies in production if any. It would also assist to understand where and how the Technology Management and/or Innovation Management units are located and organised in the hierarchy of the organisational structures as well as the associated reporting lines. The reporting lines would assist in determining the classification of roles in terms of the operational, strategic and corporate aspects, or a hybrid thereof in any combination. Secondary data would be used to arrive at a comparative assessment in terms of the identified and existing approaches of FeMn/SiMn production processes.

Over and above the approaches of the research process, reference would be made to primary sources that have defined technology over time. The strengths of this methodological research as envisaged will most likely ensure that the sources of error are identified in the overall empirical research. The inherent effects of observers’ subjectivity will be minimised. Methodological studies have occurred outside an environment of a developing country. Most of these similar studies have been conducted in the United States of America, and so the depth of knowledge robustness could be lacking. In most cases, the main sources of errors in such studies are sampling and measurement errors (Mouton, 2001).
3.4 Cases for study

3.4.1 Reference cases’ overview

It would be easy to readily look at production processes at the following organisations and programmes: P1, P2, S1, S2 and S3 as per Table 3.1. Other organisations that will be looked at for secondary information would be the equipment suppliers, and production processes within the ferroalloys industry in general. There will be a review of the corporate and projects’ documents of all the organisations. The choice of organisations identified would set the balance between the nature of ownership of enterprises and the business focus, e.g. between privately owned enterprise, sub-sector focus and size within an industry.

As already stated, the study will primarily use five key environments as reference cases for investigation: P1 – a HCFeMn producer; P2 – a silicomanganese producer; S1 – a LCFeMn and MCFeMn producer; S2 – a new HC FeMn producer; and S2 – a HCFeMn producer.

The following aspects informed the context of choosing these cases to assist the study:

- The uniqueness of the organisation and/or project: These are unique organisations either in terms of market share, unique operations, and size of a project relative to a developing country environment.

- Access to information: Focus was also placed on the ease of accessing information through all relevant media and most importantly through personal interfaces. Personal interfaces could also imply participant orientation to the organisation – P1, P2, S1 and S2 in this instance.

- Reliability of processes: It was important to use organisations that have established processes at a global scale. These processes could largely be informed by the technological paradigm being implemented. For example, P1 would be focused on HCFeMn production processes that are globally well defined.
3.4.2  **P1: HCFeMn producer – Case study 1**

3.4.2.1 Background

P1 is the largest ferromanganese producer in South Africa, operating two manganese mines in South Africa. One mine is an underground mine of hydro-thermally enriched manganese ore of a high grade. The variety in grade of ores enables manganese to offer a range of products suitable for all applications. The other mine is an opencast operation. The ore lends itself to technologically advanced beneficiation processes. P1 operates four large electric furnaces for the production of high-carbon ferromanganese. In 2012, P1 stopped producing silicomanganese through the five ladle furnaces. The total production capacity of P1 is 600,000 tonnes per annum.

Some customer sectors of P1 are specific to countries such as the service centres in South Africa, e.g. in the fabrication industries. The South African market consists of the products’ areas as per the 2008 performance as indicated in the following (AMSA, 2010):

The market segmentation in 2010 was generally as follows:

- Construction: 24.5%
- Service Centres: 23.8%
- Convertors/Re-rollers: 9.4%
- Pipes and Tubes: 14%
- Energy/Mining/Water/Chemicals: 7.7%
- Machinery and Equipment: 7.4%
- Packaging: 6.6%
- Furniture and Appliances: 1.3%

In terms of research and development dedicated to production processes, it is research and development that is indispensable for the implementation of ferromanganese products and solutions, but also to meet the following objectives:

- Cost reduction through improved productivity and reliability in the production processes
- Improved environmental performance through reduced emissions
- Increased product and by-product recycling; energy saving
- Flexibility in the use of raw materials and energy resources
The systematic study of the impact of products and processes on the environment through Life Cycle Assessment (LCA)

There are generally two types of processes that P1 strives to influence:

- Upstream process: from raw material selection to steelmaking like hot rolling operations; and
- Downstream process: from cold rolling to coating and finishing operations

The chemical compositions of Mn ores from mines operated by P1 are as follows (Olsen et al, 2007):

Table 3.2: Mn ore from Mine 1 of P1

<table>
<thead>
<tr>
<th>Element</th>
<th>Mn %</th>
<th>SiO₂%</th>
<th>Al₂O₃%</th>
<th>S%</th>
<th>P%</th>
<th>MgO%</th>
<th>CaO%</th>
<th>BaO%</th>
<th>K₂O%</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>37.8</td>
<td>4.00</td>
<td>0.50</td>
<td>0.01</td>
<td>0.02</td>
<td>3.5</td>
<td>14.7</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 3.3: Mn ore from Mine 2 of P1

<table>
<thead>
<tr>
<th>Element</th>
<th>Mn %</th>
<th>Al₂O₃%</th>
<th>S%</th>
<th>P%</th>
<th>MgO%</th>
<th>CaO%</th>
<th>BaO%</th>
<th>K₂O%</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>50.2</td>
<td>3.6</td>
<td>0.40</td>
<td>0.01</td>
<td>0.04</td>
<td>1.0</td>
<td>5.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

3.4.2.2 HC FeMn product specifications

Table 3.4: P1 Chemical composition of HCFeMn

<table>
<thead>
<tr>
<th>Element</th>
<th>Mn (%)</th>
<th>C (%)</th>
<th>Si (%)</th>
<th>S (%)</th>
<th>P (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>78 (75 min)</td>
<td>8.0 max</td>
<td>1.5 max</td>
<td>0.05 max</td>
<td>0.20 max</td>
</tr>
</tbody>
</table>
3.4.3  P2: SiMn producer – Case study 2  

3.4.3.1 Background  

P2 partly owns the third largest producer of manganese (Mn) ore in the world and the second in South Africa. In 2010, P2 produced 1.5Mt and in 2013 about 2.5Mt of Mn ore. The new manganese handling installation at the mine demonstrates how technical design factors and overall project considerations for the South African and global markets can be integrated. With the new development based on better materials handling, a total investment of R1.2 billion was made leading to full production. The mine’s customers are the alloy smelters in South Africa, Asia, China and Europe, and has 115 employees at the mine and eight at the corporate office.

The manganese mine operating on the Kalahari manganese field in the John Taole Gaetsese District Municipality in the Northern Cape province of South Africa. The mine is situated 13km south of Hotazel, 42km north of Kathu and 46km north-east of Kuruman on the farm Perth. The Kalahari manganese field is regarded as the largest manganese ore deposit globally. The field extends continuously in a north-western direction for a distance of 34km from Mamatwan Mine in the south to the Wessels and Black Rock Mines in the north. This 34-km stretch is regarded as the largest manganese ore deposit in the world (UMK, 2011).

On 17 May 2005, a prospecting right was issued for a total area of 15 200ha, and this was followed up with the issuing of a new mining order right dated 10 March 2008. A total manganese resource and reserve of 282 million and 41.3 million tonnes was identified, respectively, which was the result of a total of 361 boreholes drilled. Based on these viable reserves, the mine was developed with a capacity of 2 million tonnes per annum. There is also a potential to construct 750 000 tonnes per annum sinter plant. Construction of the remainder of the permanent infrastructure was also done in the first quarter of 2013. This includes:

- A primary and secondary crushing system – was commissioned during October 2011
- Conveyors feeding a run-of-mine (ROM) stockpile facility with reclaimers
- A screen house for screening the ore into three size fractions
- Product stockpile facilities (including two stacker/reclaimers)
- An office complex and workshop and stores facilities
The mine produces three different size fractions i.e. 0x6mm, 6x15mm and 6x75mm, and all have the same chemical specification as shown in Table 3.5:

<table>
<thead>
<tr>
<th>Element</th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>37.50</td>
<td>42.00</td>
<td>36.00</td>
</tr>
<tr>
<td>Fe</td>
<td>6.41</td>
<td>10.93</td>
<td>4.74</td>
</tr>
<tr>
<td>CaO</td>
<td>7.44</td>
<td>11.00</td>
<td>0.99</td>
</tr>
<tr>
<td>SiO₂</td>
<td>7.70</td>
<td>10.72</td>
<td>3.33</td>
</tr>
<tr>
<td>LoI</td>
<td>14.24</td>
<td>16.56</td>
<td>10.92</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.35</td>
<td>0.59</td>
<td>0.25</td>
</tr>
<tr>
<td>Ba</td>
<td>0.15</td>
<td>0.43</td>
<td>0.05</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.04</td>
<td>0.14</td>
<td>0.01</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.69</td>
<td>1.08</td>
<td>0.38</td>
</tr>
<tr>
<td>MgO</td>
<td>1.76</td>
<td>2.31</td>
<td>0.92</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.35</td>
<td>0.53</td>
<td>0.20</td>
</tr>
<tr>
<td>P</td>
<td>0.03</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>S</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>V₂O₅</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
</tr>
</tbody>
</table>

There are always foreseen challenges with the handling of manganese being a coarse and abrasive material. The new plant design would solve the known challenges such that all the three products could be availed at ease.

The new mining operation is an open pit mine with facilities in various stages of design, fabrication, erection, and operation. The final material handling system includes an ROM truck tip and crushing station, ROM stockpile, screening facilities, undersize material truck loadout, product stockyard, ISO sampling station, and train loadout.

The P2 Mn ore design specifications are shown in Table 3.6:

<table>
<thead>
<tr>
<th>Mn Ore</th>
<th>Mn, selectively mined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1,800-3,000kg/m³</td>
</tr>
<tr>
<td>ROM size</td>
<td>0-2 000mm</td>
</tr>
<tr>
<td>Product sizes</td>
<td>0-6mm, 5-15mm, 15-75mm</td>
</tr>
<tr>
<td>Operating temperatures</td>
<td>-10 to 50 C</td>
</tr>
<tr>
<td>Train consignment size</td>
<td>6,500t</td>
</tr>
</tbody>
</table>
Through the use of automated controls, closed circuit television (CCTV) observation, three-dimensional stockyard mapping software, and safety-interlocked instrumentation, the mine plant has been automated to function with limited operator interaction. The state-of-the-art materials handling facility took into consideration the materials’ wear possibilities, noting that manganese is abrasive. The automated process could be viewed by the executive management in respect of the current stockpile reserves for strategic planning purposes (Alexander, Scholtz and Tucker, 2011).

3.4.3.2 SiMn Product Specifications

![Figure 3.3: Silicomanganese (SiMn) picture](image)

<table>
<thead>
<tr>
<th>Element</th>
<th>Range</th>
<th>Specification (%)</th>
<th>Typical (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>Min</td>
<td>65</td>
<td>66.7</td>
</tr>
<tr>
<td>C</td>
<td>Max</td>
<td>2.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Si</td>
<td>Min</td>
<td>16</td>
<td>17.1</td>
</tr>
<tr>
<td>P</td>
<td>Max</td>
<td>0.15</td>
<td>0.012</td>
</tr>
<tr>
<td>S</td>
<td>Max</td>
<td>0.015</td>
<td>0.010</td>
</tr>
</tbody>
</table>

3.4.4 P3: LC and MC FeMn producer

3.4.4.1 Background

The furnace raw materials are delivered by rail and off-loaded using wagon tipplers and transported to the raw material bays by conveyor belts. Manganese ore is railed from the mines in the Northern Cape. Reductants in the form of metallurgical coke and anthracite peas are procured locally and internationally and in conjunction with the Soderberg continuously baking electrodes form the source of carbon units required for the smelting reaction. The raw materials supplied are monitored closely for phosphorous. All furnaces are controlled by Programmable Logic Controller (PLC) based supervisory systems, which optimise the power input into the furnace and enhance the operation.
Mn ore specification of mine 1:

Table 3.8: Mn ore composition of mine 1 of S1

<table>
<thead>
<tr>
<th>Element</th>
<th>37% lumpy (typical)</th>
<th>37% fines (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>37.80</td>
<td>38.0</td>
</tr>
<tr>
<td>Fe</td>
<td>5.60</td>
<td>5.40</td>
</tr>
<tr>
<td>SiO2</td>
<td>6.40</td>
<td>6.10</td>
</tr>
<tr>
<td>P</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>S</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>Al2O3</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>CaO</td>
<td>13.30</td>
<td>13.20</td>
</tr>
<tr>
<td>MgO</td>
<td>3.90</td>
<td>3.90</td>
</tr>
<tr>
<td>K2O</td>
<td>0.030</td>
<td>0.030</td>
</tr>
<tr>
<td>Na2O</td>
<td>0.040</td>
<td>0.040</td>
</tr>
<tr>
<td>B ppm</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>H2O</td>
<td>0.80</td>
<td>2.20</td>
</tr>
</tbody>
</table>

Mn ore specification mine 2:

Table 3.9: Mn ore specification at mine 2 of S1

<table>
<thead>
<tr>
<th>Element</th>
<th>42% lumpy (typical)</th>
<th>44% lumpy/fines (typical)</th>
<th>46% lumpy (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>42.50</td>
<td>44.80</td>
<td>46.50</td>
</tr>
<tr>
<td>Fe</td>
<td>12.50</td>
<td>11.00</td>
<td>10.60</td>
</tr>
<tr>
<td>SiO2</td>
<td>5.00</td>
<td>5.10</td>
<td>5.00</td>
</tr>
<tr>
<td>P</td>
<td>0.030</td>
<td>0.040</td>
<td>0.030</td>
</tr>
<tr>
<td>S</td>
<td>0.130</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>Al2O3</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>CaO</td>
<td>8.80</td>
<td>7.70</td>
<td>7.40</td>
</tr>
<tr>
<td>MgO</td>
<td>0.00</td>
<td>1.35</td>
<td>0.90</td>
</tr>
<tr>
<td>K2O</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>Na2O</td>
<td>0.030</td>
<td>0.090</td>
<td>0.070</td>
</tr>
<tr>
<td>B ppm</td>
<td>600</td>
<td>700</td>
<td>750</td>
</tr>
<tr>
<td>H2O</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
</tbody>
</table>

3.4.4.2 Product specification

The manganese ore is reduced to an iron/manganese alloy inside the furnace on a continuous basis. The slag that is fluxed with either limestone or quartzite and metal are tapped from the furnace on a periodic basis. The molten metal and slag separate as a result of density differences. The less dense slag is removed and the molten metal is then cast using either the ingot casting method or layer casting method as used by Cato Ridge Works.
Ingot casting is done by casting the molten metal into ingot trays. The metal is then cooled, crushed and sized to meet customer requirements. Layer casting is done by casting the molten metal into bays one tap at a time to form a layer of approximately 50mm thick. This is done up to twenty four (24) times, resulting in numerous layers one on top of the other forming solidified layers. During the removal of the solidified layers from the bays, the material starts breaking up due to the brittle nature of the alloy, and is then crushed and sized to meet customer specification. Slag is disposed of in such a way that it can later be recovered and re-used or rehabilitated. Table 3.8 below shows the composition of the SiMn product at P2:

![Figure 3.4: Medium Carbon Ferromanganese (MCFeMn) picture](image1)

![Figure 3.5: Low Carbon Ferromanganese (LCFeMn) picture](image2)

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>76</td>
</tr>
<tr>
<td>Fe</td>
<td>14</td>
</tr>
<tr>
<td>Si</td>
<td>&lt;1.00</td>
</tr>
<tr>
<td>C</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>S</td>
<td>6.7 – 7.2</td>
</tr>
</tbody>
</table>
3.5 Summary

Chapter 3 illustrated the research methodology to be followed for the study. The research will look into the suppliers to the SiMn/FeMn industry, experiments conducted to improve the efficiency of various production processes, observations of production processes being undertaken through site visits and secondary data analysis. There will be a lot of interactions with plant process engineers to understand their thinking behind various production activities. The study will follow a methodological research, which will be supported by content analysis since this a new study that has never been done in a developing country environment.

There are two methods of identifying what needs to be focused on from a ferromanganese production process frame of reference: life cycle assessments (LCA) of the ferroalloys production processes; and the complete mining-metallurgical value chain. Importantly, the data earmarked will use the platform of the metallurgical parameters: Mn ore compositions, Mn recovery percentage, electricity usage, load used, production tonnages and electrodes depletion. Summarily the following will be the metallurgical parameters of importance:

<table>
<thead>
<tr>
<th>Metallurgical parameter</th>
<th>Units</th>
<th>Details/Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average alloy composition</td>
<td>(%Mn, Fe, Si, C)</td>
<td>Covered in section 3.4</td>
</tr>
<tr>
<td>Average slag composition</td>
<td>(%MnO)</td>
<td></td>
</tr>
<tr>
<td>Mn metal recovered</td>
<td>(%)</td>
<td>SiMn (%); HCFeMn (%)</td>
</tr>
<tr>
<td>Mn:Fe ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy consumption</td>
<td>kWh/tonne</td>
<td></td>
</tr>
<tr>
<td>Electrode consumption</td>
<td>kg/MWh</td>
<td></td>
</tr>
</tbody>
</table>

Importantly what will also be looked at are the following:

A. Process configuration
B. Preparation of input materials
C. Handling of product
D. Savings from the operations
E. Monitoring methods

The chapter that follows will present the findings of the study.
Chapter 4

Benchmarking Techniques in SiMn/FeMn Processes

4.1 Data Overview

The utility of pyrometallurgical plants alluded to the following as advantages of why specific plant equipments especially furnaces should be suitable. A paper was published and presented at the International Ferroalloys Congress (INFACON) in Ukraine in observance of the production processes of manganese ferroalloys (Sedumedi and Pan, 2015)**:

- Availability of extensive database;
- Availability of extensive experience of industrially operated plants for various applications; and
- Availability of innovative process development based on past experience.

Figures 1.4 and 4.1 illustrate the production processes of HCFeMn (P1 facility) and SiMn (P2 facility), respectively, which are the dominant ferromanganese products consumed by the steel industry. And hence their production challenges defined suitable areas for benchmarking techniques.

**From a paper titled “Benchmarking in the Ferromanganese Production Processes” published and presented at the 14th International Ferroalloys Congress (INFACON XIV) held in Kiev, Ukraine on 01-03 June 2015.
During the metallurgical project life, process testwork was carried out at various stages, to reduce uncertainty and mitigate risks i.e. both financial and process-related. Pyrometallurgical testwork is often seen as particularly important because of the high capital cost of the plant equipment, and the serious consequences if something went wrong in the smelting plant. Some of the significant risks were: the process might require more energy than expected, metal recoveries might be lower than required, the desired process throughput might not be achieved or might not be achieved quickly enough, or the furnace might fail altogether. Pyrometallurgy practice is also confronted with the choices of configuring testwork dimensions, whether it should be large scale or should be done instead smaller with less expenses.

In Figure 4.1, the main source of Mn in raw materials for SiMn production is Mn-ore and Mn-rich slag from the high carbon FeMn production. The amount of slag per tonne of SiMn metal is mainly determined by the ore/slag ratio. Increasing share of FeMn slag at expense of Mn-ore will lead to larger slag/metal ratio in the SiMn process. High volume of slag leads to an increased consumption of energy and probably to higher losses of metal inclusions in the final slag. The distribution of Si between SiMn alloys and multicomponent MnO-SiO₂-CaO-Al₂O₃-MgO slags is mainly determined by the process temperature, the silica content of the slag and its ratio i.e.:

\[ R\text{-ratio} = \frac{(CaO+MgO)}{(Al₂O₃)} \]  \(\text{(A)}\)

As an example, the equilibrium content of Si in the alloy was found to increase by about 6% if the R-ratio is reduced from 2 to 1, provided that the temperature and silica content are constant. The effect of temperature was also considerable, and the equilibrium content of silica increased by approximately 6% per 50°C in the temperature range 1550°C to 1700°C. The equilibrium content of MnO in SiMn slags depended first of all on the temperature, and secondly on the silica content of the slag. At 1600°C the MnO content decreases from about 9% at silica saturation to a minimum of about 3-4% when the silica content is reduced to about 40-45%.

The physical properties of the Mn ore during the heating and reduction affected the furnace operation. If the semi-molten ore, containing solid MnO phase was very viscous, the ore would not flow into the coke bed. There were plant operations that focused on the temperatures that described the flow characteristics of various types of Mn ores, which was the temperature where the first liquid phase appeared, as well as the temperature where the melting ore behaves like a liquid.
The main oxide components in raw materials for silicomanganese production are MnO, SiO, CaO, MgO and Al₂O₃. MnO and SiO₂ are partially reduced whereas the more stable oxides CaO, MgO and Al₂O₃ are regarded as unreducible and will go entirely to the slag phase. Even though these oxides do not take part in the reduction process, they are of great importance for the thermodynamic and physical properties of the slag phase.

The distribution of silicon and manganese between carbon-saturated Mn-(Fe)-Si-C alloys and MnO-SiO₂-CaO-Al₂O₃-MgO slags in equilibrium with CO gas is a result of simultaneous reactions taking place. In the SiMn process the temperature may reach 1600°C or higher, and the composition of metal and slag is assumed to approach equilibrium.

The main equilibrium reactions that controls the distribution of silicon and manganese between the slag and metal alloy are the following whether the alloy was ferromanganese or silicomanganese:

\[(\text{MnO}) + \ 'C' \rightarrow \text{Mn} + \text{CO(g)} \]  \hspace{1cm} \text{(1)}

\[(\text{SiO}_2) + 2'C' \rightarrow \text{Si} + 2\text{CO(g)} \]  \hspace{1cm} \text{(2)}

Parentheses indicate species present in the slag phase and underscored species in the alloy. 'C' is carbon either as graphite or in silicon carbide dependent on the Si-content of the alloy. Graphite is the stable phase coexisting with liquid Mn-Fe-Si alloy until the Si-content reaches a certain value, approx. 17-18% Si, somewhat dependent on the temperature and the Fe-content of the alloy. At higher Si-contents silicon carbide is the stable coexisting phase. In the following the term "carbon saturated" or \(C_{\text{saturated}}\) is relevant with either graphite or silicon carbide.

Complete slag/metal/gas equilibrium required simultaneous establishment of equilibrium for the two reactions (1) and (2). Both reactions are very dependent on the temperature and the CO pressure of the system. Higher temperatures will give higher equilibrium content of Si in the metal and lower MnO content in the slag. A low CO pressure will also favour higher content of Si in the metal and less MnO in the slag. Normally the CO pressure is quite close to 1 atm in electric submerged arc furnaces. Partial pressures of CO, SiO₂ and Mn above Mn-Si-C\(C_{\text{saturated}}\) alloy in equilibrium with SiO₂-saturated slags are available for various FeMn/SiMn reaction conditions.
A combination of the two reactions (1) and (2) above therefore gives the partial slag/metal equilibrium reaction, expressed by:

\[ 2(\text{MnO}) + \text{Si} \rightarrow 2\text{Mn} + (\text{SiO}_2) \] (3)

High process temperatures were required to produce silicomanganese alloys by carbothermal reduction of the oxide ores; even so for medium-grade ores. The SiMn slag is a throwaway product, and loss of manganese, both as MnO and as metal inclusions in the slag, has considerable economic consequences. At complete equilibrium, the following equation at the cokebed zone has to be:

\[ \text{MnO} + 'C' \rightarrow \text{Mn} + \text{CO} \] (4)

\[ K_T = \frac{(a_{\text{Mn}} \cdot p_{\text{CO}})}{(a_{\text{MnO}} \cdot a_{'C'})} \] (B)

\( K_T \) is the equilibrium constant at temperature T. The equilibrium content of MnO in the slag is mainly dependent on the temperature, the CO pressure, and also on the slag composition influencing the activity coefficient of MnO.

The effect of Al\(_2\)O\(_3\) and MgO on equilibrium relations has been evaluated at various SiMn producers. Alumina is characterised as an amphoteric oxide. When added to acid slags, Al\(_2\)O\(_3\) will act as a basic component and give lower MnO contents, and addition to more basic slags will have the opposite effect. The change between ‘acid’ and ‘basic’ slags took place at about 45% SiO\(_2\). For a typical SiMn slag with about 40% SiO\(_2\) the overall effect of increasing Al\(_2\)O\(_3\) at the expense of CaO was to give an increased equilibrium content of MnO in the slag. The effect of MgO on equilibrium relations was less important. It was found that MnO in the slag is slightly increased when some CaO was replaced with MgO.

In the solid state, the higher manganese oxides were reduced from MnO\(_2\) and Mn\(_2\)O\(_3\) to Mn\(_3\)O\(_4\) and MnO, when heated in CO gas. At 1100-1200ºC, acid ores like Comilog ore may be presented in the MnO-SiO\(_2\)-Al\(_2\)O\(_3\) phase diagram. As the temperature increases, the first liquid phase in the ore will be present at less than 1300ºC. At this temperature, the ore will contain a solid MnO phase in coexistence with a liquid phase. As the temperature continues to increase, the reduction will start and the MnO content decreases. Both the increasing temperature and the lower MnO content lead to a lower content of solid MnO phase. At a certain degree of reduction, the slag would be completely liquid.
From Figure 4.2, the physical properties of the Mn ore during the heating and reduction affected the furnace operation. If the semi-molten ore, containing solid MnO phase, was very viscous, the ore will not flow into the coke bed. This benchmarking work is focusing on the temperatures that will describe the flow characteristics of various ores, which is the temperature where the first liquid phase appeared, as well as the temperature where the melting ore behaved like a liquid (Kalenga, Pan and Tangstad, 2013).

The amount of slag per tonne of SiMn metal is mainly determined by the ore/slag ratio. Increasing share of SiMn/FeMn slag at the expense of Mn-ore will lead to larger slag/metal ratio in the SiMn process. High volume of slag leads to an increased consumption of energy and probably to higher losses of metal inclusions in the final slag. The equilibrium content of MnO in SiMn slags depends first of all on the temperature and secondly on the silica content of the slag. At 1600°C the equilibrium content of MnO decreased from about 9% at silica saturation to a minimum of about 3-4% when the silica content was reduced to about 40-45%. The distribution of Si between SiMn alloys and multicomponent MnO-SiO2-CaO-Al2O3-MgO slags was mainly determined by the process temperature, the silica content of the slag and its R-ratio:

$$R\text{-ratio} = \frac{(CaO+MgO)}{Al_2O_3}$$
4.2 Benchmarking Data Articulation

The study attempted to identify the variables that influence the production process of manganese ferroalloys. It was important to identify the main dependent variables in the operational areas of a ferromanganese plant to identify the process benchmarking techniques. The main SiMn/FeMn plant operational areas were observed to be the following:

- Materials preparation
- Furnace operations
- Cooling operations
- Comminution operations
- Marketing activities

It was established that most bottlenecks were related to the following:

- Increasing production measured by FeMn/SiMn tonnes per day (tpd)
- Decreasing operational costs measured by rands per tonne (R/t)
- Being environmentally friendly measured in mg.m\(^{-3}\)
- Being safety conscious measured by Lost Time Injury Frequency Rate (LTIFR)

The correlation in terms of risk profiling between the operational areas and bottlenecks can be represented as follows:

<table>
<thead>
<tr>
<th>Bottlenecks</th>
<th>Productivity</th>
<th>Costs</th>
<th>Environment</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Furnace</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Cooling</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Comminution</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Marketing</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

It will be important to analyse the seven high-risk areas in the production operational processes of manganese ferroalloy plants. The furnace operations were all high-risk in respect of the operational performance of the entire plant, and the marketing operations were low-risk on average. Medium-risk areas could turn lower or higher depending on how external factors are handled like access to good Mn ore and reductants, investments in pelletising or briquetting, and product logistics.
4.2.1 Process value chain
The process value chain recognises the various elements involved in the operational areas of the plant. Importantly it is the type of equipment used and how it is optimally deployed. Because of productivity improvements and encouraging the economies of scale, larger or more furnaces were now preferred. However larger furnaces come with challenges such as on operational stability, balancing of electro-thermal variables like voltage and current strength, charge resistivity, and kinetic control.

Materials were prepared as daily feeds like at P1 and P2 or as three to five day cyclical feeds. The frequency of preparation and the source of the material had an effect on the reliability of the charge to be fed. At P2 the charging was decentralised as compared to P1, which was similar to their automated control rooms. There was much electro-thermal instability at P1 as compared to P2, largely due to the size of the furnaces that required longer electrode diameters. Hence P1 had excessive emissions as compared to P2, which were almost non-existent.

4.2.2 Life cycle assessment
Life cycle assessment of production processes of manganese ferroalloys was based on the high risk factors as in Table 4.1. The high-risk factors were the following:

- Influence of materials preparation on increasing the rate of production;
- Influence of furnace operations on productivity, costs, environment and safety;
- Influence of cooling operations on production rate, and safety measures; and
- Influence of comminution on the rate of production.

Therefore it would seem that the rate of production was an intrinsic factor that would need careful consideration. The production of manganese ferroalloys in electric furnaces was based on a staged materials and energy balance. Attention was also focused on coke and energy consumption dependent on available oxygen in the manganese ore, relative reactivities of manganese ore and coke, and on moisture content and decomposition of carbonate fluxes.

The importance of the energy consuming Boudouard reaction i.e.:

\[
\text{CO}_2(\text{g}) + \text{C} \rightarrow 2\text{CO}(\text{g}),
\]

cannot be over emphasised. Manganese vapour and alkali circulation contributed considerably to energy transfer within the furnace, carrying energy from the hot smelting zone to the colder zones where solid-state reduction takes place.
4.3 FeMn/SiMn Production processes’ observations

4.3.1 Process outcomes
The main South African manganese ferroalloy producers were reliably surveyed and the following were the results thereof from the process factors:

Table 4.2: Benchmarking variables of reference cases P1 and P2

<table>
<thead>
<tr>
<th>Variables</th>
<th>Relational factors</th>
<th>P1</th>
<th>P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore supply</td>
<td>P1 and P2 are facing some challenges in Mn ore grade control</td>
<td>Silicate and oxide Mn ores reliably supplied from the Kalahari fields</td>
<td>Carbonaceous Silicate Mn ore reliably supplied from the Kalahari fields</td>
</tr>
<tr>
<td>Reductant supply</td>
<td>Local reductant sources of a good quality are getting fewer</td>
<td>Supplied from a variety of metallurgical coal sources</td>
<td>Supplied from the Witbank coalfields</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>Electricity production could contribute to the majority of impact on the environment. Direct emissions are within direct control</td>
<td>Power of 20MW is generated from off-gas</td>
<td>Influenced by the invariable quality of ore supply; hence requiring more additions of quartz as flux</td>
</tr>
<tr>
<td>Environmental conditions</td>
<td>Gas emissions</td>
<td>- Moderate control</td>
<td>- Good control</td>
</tr>
<tr>
<td></td>
<td>Dust emissions</td>
<td>- Poor control</td>
<td>- Good control</td>
</tr>
<tr>
<td></td>
<td>Solid waste</td>
<td>- Good control</td>
<td>- Good control</td>
</tr>
<tr>
<td>Metal recovery</td>
<td>Secondary furnaces</td>
<td>- Ladies’ usage</td>
<td>- No ladles used</td>
</tr>
<tr>
<td></td>
<td>Casting</td>
<td>- Sand casting</td>
<td>- Layer casting</td>
</tr>
<tr>
<td></td>
<td>Crushing</td>
<td>- Standard</td>
<td>- Standard</td>
</tr>
<tr>
<td>Salient factors</td>
<td>Key parameters</td>
<td>HCFeMn: 5 furnaces, 250MVA</td>
<td>SiMn: 5 furnaces, 150MVA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 x Control room 610,000 t/a</td>
<td>5 x Control rooms 180,000 t/a</td>
</tr>
</tbody>
</table>

4.3.2 Production parameters
The study has pointed to the rate of production as the single most important factor that any benchmarking technique must consider. Any production process has to be viewed from what aspects would increase the production rate, and then adjust any other variables accordingly. It would lead to new production modeling because the kinetic control of furnace operations is also dependent on technical processes before and during the furnace operational process. Processes before are the preparation of materials; and processes during are the adjustment of load and charge fed through electrode control. Furthermore, the required rate of production has to influence the safety requirements, cost control measures, and the environmental controls.
4.4 Benchmarking the rate of production

The process performance of the production SiMn/FeMn was dependent on the generation and transfer of heat in the furnace. It increases the rate of metal production, and at the core of the rate of production is how the furnace operations were configured and conducted. These operations are at a preparatory level of charge, and what happens during the smelting process. Hence there is a need to understand the material and heat balance of the production process. In general, the furnace consists of two reaction areas i.e. the reduction area and the coke-bed area.

The following had been verified in terms of the staged material and heat balance of the Comilog ore chemical behaviour, and thus the furnace is divided in four zones, which are defined as follows:

**Zone 1:** *Drying and calcination zone*, including the low temperature reduction $\text{MnO}_2 \rightarrow \text{Mn}_2\text{O}_3$. Some hydrogen formation by the watergas reaction. $\text{MgCO}_3$ in dolomitic limestone is decomposed.

**Zone 2:** *Gas reduction zone* where $\text{Mn}_2\text{O}_3$ is reduced to $\text{Mn}_3\text{O}_4$ and partly to $\text{MnO}$.

**Zone 3:** *Direct reduction zone* where Mn-ore reduction and the Boudouard reaction run simultaneously. Iron oxide is reduced; $\text{Fe}_3\text{O}_4$ to $\text{Fe}$, and $\text{CaCO}_3$ in dolomitic limestone is decomposed.

**Zone 4:** *Smelting reduction zone* where $\text{MnO}$ dissolved in slag is partly reduced to liquid metal. Some silica is also reduced, and some carbon is dissolved in the metal.

Zones 1 – 3 corresponded to the pre-reduction area, and Zone 4 to the cokebed area. The main factors that affected the heat distribution and the process temperature were the following:

- Electrical energy supply
- Enthalpy of chemical reactions – energy consuming and energy producing reactions
- Transfer of heat by circulating matters e.g. $\text{Mn}(g)$ and $\text{K}(g)$
- Heat exchange between solid and solid materials

The energy consumption per tonne of SiMn/FeMn produced was dependent on the reactions at the pre-reduction areas. In the cokebed area, the energy consumption was more stable, and any variations observed were dependent on the conditions in
the pre-reduction area. The variations were confirmed to be divided into two categories:

- Variations in energy consumption with fixed raw material composition which was due to: high water content in the burden, content of fines, and the size of the pre-reduction area influencing the retention time of the pre-heated ore in contact with the CO gas; and

- Variations due to changes in raw material composition: CO gas reduction of the higher manganese oxides are exothermic reactions, with higher oxygen level in the ore giving lower energy consumption. Therefore, ores high in MnO₂ gave lower energy consumption than Mn₂O₃ and Mn₃O₄.

The rate of reduction was controlled by the temperature, the partial pressures of CO and CO₂, and the Mn ore reactivity. With respect to the Mn ore, the important variables are the reactivity and the mechanical strength. In addition, a reducing furnace environment was found not to be suitable in increasing the reduction rates as compared to an inert environment. The reduction rate was determined by the mass transfer: diffusion of reactant gases in, and product gases out of the reaction zone was found to determine the reaction rate. Hence the high quality reductant was important to provide suitable partial pressures of CO and CO₂.

In all the cases, the reduction of higher oxides to MnO was found to be affected by the original mineral composition. In addition, porosity, sizing and chemical composition were also critical elements, but the reduction rate was different for each ore, and even between particles of a given ore. Therefore it was important to understand the mineralogy of the Mn ore in detail to substantiate the reactivity and mechanical properties. For example, when investigating the mechanical strength of Mn ores, there were two aspects that were confirmed from previous research work:

- Degradation of the ore when transported to the furnace; and
- Degradation of the ore inside the furnace during heating and reduction.

It has been shown that Mn ores in general were much more fragile when heated in a reducing environment as compared to when being heated in an inert or oxidising atmosphere. From studies, it is also known that the Mamatwan and Wessels ores (mostly carbonate silicate ores) had a greater mechanical strength than the Comilog and Groote Eylandt ores (oxide ores). The latter ores were better at reactivity.
4.5 Benchmarking observations

Process benchmarking was consistent with the productivity measure in considering the production rate as a key and determinant process variable. The production rate determined the performance of the SiMn/FeMn production process. Other variables from the data were the production costs, equipment innovation, environmental factors and safety considerations.

4.5.1 Furnace equipment innovations

One of the equipment suppliers patented and copy-protected innovations on closed submerged arc furnaces for ferroalloys with the use of copper centre panels for the furnace roof to replace the traditional stainless steel sections. The high electrode currents around 150,000A caused eddy currents to flow in the metal sections of the roof panels, causing them to heat up. Stainless steel is less electrically conductive than copper, but it has very poor heat conductivity. Copper being up to 25 times more conductive than stainless steel, is much better for handling of the heat generated in the furnace, which resulted in extended life of the furnace roof. With furnace temperatures of around 2,000°C the temperature of copper panels could be kept below 100°C as compared to a stainless temperature of 220°C under the same conditions. The thermal expansion of stainless steel resulted in panels leaking and bursting, so by using copper ones instead, there were savings in downtime and repairs.

Another South African technology was the use of pressure rings, used to push the contact shoes onto the furnace electrodes to prevent arcing. These electrodes could be up to 1.9 metres in diameter. The pressure ring design was covered by three international patents: the material construction; the C-clamp mechanism used to join sections together, and the lower tip seal. This equipment supplier is now the dominant supplier of these pressure rings to the ferroalloys market. Pressure rings are the most important piece of equipment, and key components of a furnace.

Pressure rings have traditionally been troublesome during the operation of an electric submerged arc furnace using the Soderberg-type of electrodes, which required that the electrodes be supported at the lowest possible point, precariously close to the flames blowing up the side of the electrodes. The design was now being successfully used in many furnaces in South Africa. Furnaces operate on a 24-hour-basis, and just a few hours of downtime quickly adds up to millions in lost production revenue. When traditional pressure rings failed, it could take up to 24 hours to replace, with personnel constantly working in potentially dangerous conditions.
The pressure rings were designed for ease of fitment and removal. This reduced the downtime to replace existing pressure rings. Failures from the previous pressure rings, due to cracks and the bending open of the skirts, exposed and stressed the expansion bellows. The pressure rings have offered a solution. They were also easy to assemble and disassemble and experienced better baking of the electrodes.

4.5.2 Electrical consumption
There were currently projects of smelter upgradings because ferroalloy producers were told by the government to cut production because of power shortages. With the market as evaluated periodically, SiMn/FeMn plants were stopping production, which was taking the pressure off. But it turned around again, and ferroalloy producers were looking at ways of reducing their power consumption as well as increasing output. It was an ideal time for plants to shutdown in order to modernise or upgrade.

It meant growth in the covered furnace and sinter plant business to reduce both undesirable emissions and power consumption. SiMn/FeMn organisations were also looking at power regeneration projects, using the hot gas produced by the closed furnaces to produce steam for small turbine generator sets, a new opportunity for the equipment suppliers. And P1 was already producing 20MW of its own power.

During the production of ferro alloys in electric smelting furnace, a lot of heat energy is being wasted through flue gases which was being discharged to the atmosphere at a temperature as high as 500-900°C. Gas evolved in the operation was 700 to 1000 NM³/tonne of alloy. The figure varies with the type of alloy produced. Temperature of flue gas and volume of gas evolved in case of SiMn/FeMn was much higher. Hence rich fuel gas with a calorific value of 2000-2500 KCal/M³ was evolved from a ferromanganese furnace, which was being wasted to atmosphere. If heat evolved was utilised economically for drying of wet charge, steam generation or pre-reduction energy saving could be achieved.

4.5.2.1 Furnace operation process:
In order to obtain lower power consumption, the correct operating schedule had to be followed; for production of FeMn flux or semiflux technique of production was followed. Whatever may be the technique for particular MnO in slag, proper basicity should be chosen for which slag composition should be closely controlled. Movement and position of electrode in the charge affect furnace operation. Movement of electrodes depends upon resistivity of charge, which in turn depends upon metallic
and non-metallic content of the charge. For good operating schedule and less heat loss, deep electrode penetration in the charge was generally practised. Furnaces were in general run on a lower secondary voltage. This kept the electrodes down with reduced heat loss, and avoided excessive heating and thereby volatilisation loss of Mn leading to reduction in specific power consumption.

Frequent taphole opening and closing was practised, and should generally be avoided. So the number of tappings should be reduced by taking them at higher power consumption. This will avoid wastage of heat. Heat loss due to circulating water could be reduced by reducing the flue gas temperature, which can be reduced by proper control of furnace charge, use of beneficiated charge with lower fines content, increasing height of charge and by constantly covering the electrode with the charge.

4.5.2.2 Pre-heating and Pre-reduction process:
At some of the ferroalloy plants, preheating and pre-reduction of charge was being practised. Flue gas temperature of closed electric smelting furnace for production of FeMn is around 500°C. As an example, for 9MVA furnace about 35,000 NM³/day of gas passes to the atmosphere. Hence lot of heat energy is wasted to the atmosphere. Calorific value of the gas is around 1900 KCal/M³. Attempts have been made for the use of flue gas for preheating of charge by increasing pressure under furnace cover. And the flue gas was allowed to pass through the shaft carrying the charge. Shaft preheating is done by counter current heating of the charge by combustion of clean furnace gas.

In the case of FeMn/SiMn production, preheating and pre-reduction takes place at the upper layer of the smelting furnace charge, and less benefit was derived. Most losses could be reduced by reducing flue gas temperature by increasing the charge height. In such a case the flue gases have to pass through a greater charge volume, which will transfer sensible heat to the charge. For achieving this furnace design modifications have to be done suitably.

4.5.2.3 Preparation of raw material:
Most of the raw materials are brittle and during handling generate fines. Fines are detrimental for electric smelting furnaces. These fines reduce the porosity of charge. They also carry higher quantity of gangue material. Coke fines being lighter are easily carried away by the gases. They affect the permeability of charge to a greater degree than that of manganese ore fines. Apart from fines, the oversize fractions of
charge also needs to be controlled closely. Ideal size of Mn ore feed for furnace is 3mm to 70mm with +4-5 to -10mm and +50 to -70mm size fraction not to exceed 15%. Similarly, size of coke should also be controlled. Different fractions of coke not only affect the porosity of charge but also affect the position of electrode inside the charge, resistance of charge, and the resultant heat distribution inside the furnace. Proportions of breeze coke (5mm to 10mm) and nut coke (10mm to 25mm size) should be properly controlled so as to promote favourable furnace condition. Hence proper screening of ores before charging was of paramount importance. And it will improve the furnace performance, and hence the overall SiMn/FeMn process performance.

4.5.2.4 Use of agglomerated fines:
Sintering was the most widely used as a method of agglomeration of fines for charging in furnace. There are some advantages of use of sinter as part of burden for smelting furnace. Use of sinter increases permeability of bed, thereby uniform distribution of flue gas. Mn Ore fines can be beneficiated before agglomeration; hence SiO₂ content can be reduced. But since coke is added in production of sinter, it could increase the impurities.

During sintering higher oxides of manganese are reduced to lower oxides. Reduction of MnO₂ to lower oxide is an exothermic reaction. So by use of sinter the exothermic reaction that would have taken place by use of lumpy ore would be absent. Hence electric arc sinter practice consumes more power than when the burden is composed of lumpy ore only. In actual practice the increase in porosity of charge affects increased power. And ultimately there is reduction in specific power consumption. Use of sinter to the extent of 30-35% of the charge is recommended for optimum power consumption.

4.5.2.5 Slag composition:
Composition of slag affected the melting point as well as viscosity of slag. For better slag-metal separation, the viscosity of slag should be necessarily a minimum to avoid the loss of metal in it. In order to control the composition of slag, the chemical composition of the charge as well as the proportion of Mn ore to coke in burden should be controlled. Melting point of slag is determined by its composition and basicity. The melting point of slag should be controlled between 1350°C to 1500°C.

Electrical conductivity should be as low as possible to encourage high operating resistance. The nature of the slag composition should necessarily be between low
viscosity and low electrical conductivity. If the melting point of slag increases there will be high volatilisation loss of Mn. Slags with higher basicity have higher melting point than acid slags. In flux technique with the basicity of the slag more than 1.0% Mn in slag is very low and more Si passes in metal thereby increasing power consuming reactions. Moreover, in such operations less variation in slag basicity is tolerated. If slag basicity is less than 0.5, more %MnO goes in slag and reduction of MnO from slag becomes difficult. Hence from practical experience it was observed that 25/30% MnO in slag with 0.70 to 0.8 basicity promotes stable operation and less susceptible to changes in viscosity due to changes in slag composition. Hence power consumption was also kept down by choosing proper %MnO in slag as well as basicity of slag.

4.5.2.6 Effect of moisture:
Moisture content in charge affected furnace conditions very adversely. Increased moisture content in charge not only takes more power for evaporation of moisture but also increases power due to poor furnace operating condition. With the increase in moisture, screenability of the charge is reduced due to blockage of the screen opening. Hence the fines would pass through along with charges in the furnace without being screened. These fines carry more moisture than lumpy ore. Hence porosity of charge is reduced, resulting in crust and bridge formation inside the furnace. This affects uniform descend of the charge, uniform passage of flue gas and heat distribution inside the furnace.

The moisture content in coke varies widely which could lead to the disturbance in the carbon balance in the burden. If the burden is disturbed, it affects the slag composition, and thereby the melting point. Thus due to variation in moisture furnace operation is also affected. Increase in 1kg of moisture increases power by 1Kwh approximately. Further there is increase in power due to dissociation of water in the presence of carbon leading to endothermic reaction. There will be further increase in power consumption due to adverse furnace condition. Hence moisture content in the charge should be controlled. Coke absorbs around 15% maximum moisture. If coke is dried before charging in furnaces, not only the moisture content in furnace is reduced but also the burden control can be properly exercised. Apart from the water content in charge water due to leakage inside the furnace should also be checked in order to control increase in power consumption. Hence all precautions should be taken to avoid water leakages inside furnace.
4.6 Summary
The techniques of benchmarking of SiMn/FeMn production technologies could be practised amongst top performing ferromanganese organisations. It is feasible because many business processes are essentially the same from ferroalloy sector to sector. Benchmarking focused on the improvement of production-related business processes by exploiting best practices rather than merely measuring the best performances. Best practices were the cause of best performance at the level of processes. SiMn/FeMn organisations focusing on processes’ best practices had the greatest opportunity for gaining a strategic, operational, and financial advantage.

The systematic discipline of benchmarking was focused on the general metallurgical parameters and by identifying, studying, analysing, and adapting best practices and implementing the results. To consistently get the most value from the benchmarking process, operational leadership and senior management may discover the need for a significant culture change. That change, however, unleashes benchmarking’s full potential to generate large production improvements and strategic advantage. In evaluating the processes of producing the SiMn/FeMn, it was found to be dependent on the furnace operations. Hence the benchmarking technique considered in this study is at the level of a process of producing SiMn/FeMn. The furnace operations were a limiting factor in achieving the required productivity in terms of the rate of production. This rate of production was a function of the following: selection and preparation of Mn ores, and selection and preparation of reductants, which relied on supply of electrical power. Chapter 5 will elaborate on the key findings to yield the analysis of production processes.

Furthermore, the rate of SiMn/FeMn production was a kinetically controlled production process. The rate of reduction of Mn ores particularly of high oxide ores at the pre-reduction zones was the key bottleneck in respect of the furnace operations. Benchmarking of ferromanganese production processes entailed the gathering of information from other organisations for the benefit of the similar organisations and sectors. The process parameters were influenced by the required production improvements with the requisite production costs, and the diligent definition of the unit production costs. What was found to broadly impact on the production rate, and thus the process-related benchmarking techniques, were the following: (1) Firmed-up production capacity, (2) Optimal configuration of input materials, (3) Potential operational savings, (4) Accountability on production unit, and (5) Confidence about technological-knowhow.
Chapter 5

Yield of Manganese Ferroalloys Benchmarking

5.1 Achievements of benchmarking approach

The study found that there are 5 aspects that required to be considered when tackling the techniques of benchmarking the ferromanganese production and in determining the performance of process – as in Table 5.1 below.

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Critical details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production context</td>
<td>Key Performance Indicators and efficiency measures</td>
</tr>
<tr>
<td>Input materials configuration</td>
<td>Mn ore blending and reductant preparation and measures</td>
</tr>
<tr>
<td>Potential operational savings</td>
<td>Installed technologies and production platforms</td>
</tr>
<tr>
<td>Production unit accountability</td>
<td>Metallurgical parameters management and measures</td>
</tr>
<tr>
<td>Technology know-how</td>
<td>Metallurgical parameters management and stoichiometry</td>
</tr>
</tbody>
</table>

5.1.1 General production context

It was important for the plants to decide on the production capacities they will undertake both in the short-term and long-term, and the markets they will serve. This decision will assist to concentrate on a few constraints emanating from the input dimension. From the known production efficiency models, it was important for the input efficiencies of the SiMn/FeMn plant to be clearly conceptualised. Plant engineers compared the performance of their respective organisations, products and processes externally with competitors and best-in-class companies and internally with other operations within their own organisations that performed similar activities.

The first task in a benchmarking exercise is, therefore, to select an aspect of a process to benchmark and to consider what may be appropriate key performance metrics. Next, organisations must choose production processes to benchmark against and collect data on the performance and practices of these. Once the data are available, they must be analysed to understand the organisations’ production performance and relative cost position and possible strategic advantages. It would assist to identify opportunities for improvement and to increase organisation learning by bringing new ideas to the organisation or facilitating experience sharing.
5.1.1.1 Key performance indicators

Traditional benchmarking is centred on Key Performance Indicators (KPIs). KPIs are numbers that are assumed to reflect the purpose of the plant in some essential way. KPIs are widely used by plants, researchers and others with an interest in performance evaluation. Well-known KPIs are related to the analysis of financial accounts. They include, for example, indicators like Return on Assets (= net income/total assets), Gross Margin (gross profit/net sales), Debt Ratio (total liabilities/total assets), and Price/Book (stock capitalisation/book values). The financial indicators could be used across many industries to compare plant performances. In most industries, and for more specific processes, there are other more specific indicators that reflect the details of the technology involved.

It was observed that the plants being analysed, did well in terms of the percentage of products put in the market in the previous years where it was on par with the best practices. The plants that performed poorly on the other hand was in terms of the percentage of new products/service development projects that were launched on time. In this dimension, the plants being examined would have fared below the bottom performers. As it could be suggested, a KPI is often the ratio of an output to an input, say net income per asset. In such cases, we would like to have a large KPI.

To illustrate how such a ratio is obtained and used, let us assume that we have input–output data from several ferromanganese production plants. When we display the input–output combinations for each plant, the plant with the highest output per input is P1. For other plants to have the same KPI they must reconsider the capitalisation of the plants and surrounding infrastructure. It is important to observe that the traditional use of KPIs is based on some implicit assumptions.

Firstly, when a comparison is made of a plant with small output to a plant with large output like P1 and P2, we implicitly assume that we can scale input and output proportionally. That is, it is assumed constant returns to scale. It is assumed for example that the income per asset does not depend on the size of the plants. Small plants are assumed to generate the same net income per asset as large plants. In reality this may not be possible. Some assets may be needed before any net income can be generated such that small plants are handicapped and constrained when it comes to getting a large KPI. They cannot be in a position to utilise economies of scale to be capacititated in terms of procurement of input materials and electricity supply.
Similarly, very large plants may be handicapped by complicated coordination and control problems. If instead it is assumed increasing returns to scale, i.e. disadvantages of being small, P1 may be doing just as well as P2. Similarly, if it is assumed diminishing returns to scale, i.e. disadvantages of being large, P2 may be doing just fine.

A second limitation of the KPI approach is that it typically involves only partial evaluations. One KPI may not fully reflect the purpose of the plant. There could be multiple inputs and, therefore, forming several output-input ratios as above. And there may, for example, be interest in the output in proportion to both the input materials and capital used in the production. If this is the case, there will be two KPIs. The problem now is that the KPIs may not identify the same in most productive plants. In many cases, however, this ideal is not feasible because there will be a substitution effect in the relationship between input materials and capital usage.

More input materials allows compensation for less capital, and more capital allows to compensate for less input materials. Therefore partial benchmarks may create misleading comparisons by ignoring the interaction between production factors. A similar example could easily be constructed on the output side which suggest that partial benchmarks also ignore a possible interaction between services and products generated. Either way, the consequence is that real plant process could be judged based on unfeasible, overly optimistic ideals.

A third and more intricate limitation of simple indicator approaches is known as the Fox’s Paradox. It shows—in loose terms—that even if one plant like P2 displays higher values for all of its partial productivity measures than P1, P2 may have lower total productivity than P1. The reason is that for a plant to perform well in total, it must not only perform the different sub-processes well but also make use of the sub-processes that have relatively higher productivity.

The interpretations of the numbers for P1 and S1 are similar. It can be observed that the unit costs, UC, i.e. the cost per unit served, is smaller in P1. Still, the total unit costs in P1 are higher than in S1. The reason is that S1 relies more on the relatively less costly sub-process of self-generating power by steam coal. To sum up, the study has illustrated that simple KPIs are not sufficient to make appropriate benchmarks. KPIs often invoke implicit, strong, and unrealistic assumptions like constant returns to scale and lack of substitution possibilities between different inputs and outputs.
5.1.1.2 Efficiency measures

It is known that: Inefficiency = (Actual cost - Minimal cost)/Actual cost

Likewise, we can measure efficiency directly as the ratio of minimal costs to actual costs: Efficiency = Minimal cost/Actual cost = 1 - Inefficiency

When efficiency is high, i.e. when inefficiency is low, the production process is performing well. It is observed, therefore, that if the actual behaviour of the plant is known, here represented by output and cost numbers, and have an appropriate model of ideal performance, here represented by a cost function, performances could easily be evaluated. It could be referred to as the rational ideal evaluation i.e. it is rational in the economic meaning of rationality: Preferences involved could be specified e.g. cost reduction and the possibilities e.g. as given by the cost function, and the optimal performance as a matter of cost minimisation could be considered. Also, this form of evaluation is ideal in the sense that all of the relevant information is existent. In general, rational ideal evaluations could be described as follows. From a standard microeconomic perspective, a plant’s process performance is reflected in its ability to choose the best means (alternatives) to pursue its production aims (preferences):

Effectiveness = Actual performance/Best possible performance in

\[ T = \frac{U(Actual)}{U(Ideal)} \]

Note that the study refers to effectiveness when working with an objective function and, therefore, could refer explicitly to goal attainment. When this is not the case and relying on proxy objectives, reference is instead made to efficiency. In real evaluations like a plant process, it is not entirely easy to employ this microeconomic approach. In the typical evaluation, there is a lack of clear priorities U and clear information about the production possibilities T. In real evaluations, therefore, none of the elements in the rational ideal evaluation are known upfront.

Despite this limitation, the idea of a rational ideal evaluation could be a useful concept. Essentially, benchmarking is an attempt to approximate the idea of a rational ideal evaluation. In benchmarking, we therefore need to collect data to describe actual behaviour, approximate the ideal relationship between inputs (or inputs aggregate as in the study) and output and combine actual performance with ideal performance to evaluate efficiency.
Efficient production:

Efficiency production could be described by the Farrell’s’ efficiency approach: it is proportionality based like the KPIs. The study only considered the directional efficiency approaches:

Discretionary and non-discretionary inputs and outputs. In plant applications, situations often exist in which some of the inputs or some of the outputs are fixed and uncontrollable, at least in the short run or when using the discretionary power of the plants that is being evaluated. A very simple but useful way to handle such situations is to only look for improvements in the discretionary (controllable) dimensions. That is, the plant is held accountable for what it can control. The inputs here are divided into fixed inputs, FI, and variable inputs, VA, and we only measure how much we could reduce the variable inputs.

The approach whereby some variables are allowed to be discretionary (variable) and some to be non-discretionary (fixed) is sometimes referred to as a sub-vector efficiency approach. It is true for this study because the electricity and the output level is assumed fixed.

Therefore the logic of the sub-vector approach could be extended by using the so-called directional distance functions that allows for improvements in any direction in the input–output space. Rather than assuming that some inputs or outputs are non-discretionary and the others are discretionary, the directional approach allows for varying degrees of discretion. It enables the SiMn/FeMn plant to take into account that some inputs and outputs are easier or more desirable to modify than others. In simplifying this exposition, the study focused on the input side. On the input side, the purpose of directional distance functions was to determine improvements in a given direction \( d \) and to measure the distance to the frontier.

Cost and input allocative efficiency:

\[
c = wx
\]

where \( c \) is the cost, \( w \) the input price, and \( x \) the replica-factor. If there are \( m \) inputs,

\[
c = w_1x_1 + w_2x_2 + w_3x_3 + \ldots + w_mx_m
\]
TE = Minimal input/Actual input = Length of x~/Length of x

CE = Minimal cost/Actual cost = wx*/wx

AE = Cost of x*/Cost of x˜ = wx*/wx˜

Therefore:

Cost efficiency = (Allocative Efficiency) x (Technical Efficiency)
or

CE = AE X TE

5.1.2 Configuration of input materials

Ideal size of Mn ore feed for furnace is 3mm to 70mm with +4-5 to -10mm, and +50 to -70mm size fraction not to exceed 15%. Similarly, size of coke should also be controlled. Different fractions of coke not only affected the porosity of charge but also they also affect the position of the electrode inside the charge, resistance of charge, and the resultant heat distribution inside the furnace. Proportions of breeze coke (5mm to 10mm) and nut coke (10mm to 25mm size) should be properly controlled so as to promote favourable furnace condition. Hence the proper screening of ores before charging was of paramount importance. And it will improve the furnace performance, and hence the overall FeMn/SiMn process performance.

5.1.3 Potential operational savings

Installed technologies are usually the furnace design methodologies excluding the Mn ore blending methods. One of the widely used ore preparation methods in South Africa is sintering due to the encountered low-grade ores in the Kalahari manganese fields. The production SiMn/FeMn occurs on a scale that does not allow the use of large sinter plants at a SiMn/FeMn plants. Hence the sintering of fines is often carried out at the mine. In Table 5.1 below it is illustrated the typical Mn ore and Mn sinter product transformations for better Mn ore blending.

Other plants like the Tokushima Plant of Nippon Denko Co. Ltd. developed a high-temperature electrical conductivity measuring system that can evaluate the electrical conductivity of material ores in the high-temperature region. Using this measuring system, the high-temperature electric characteristics of various lump ores were evaluated. Standards were established for determining ores and blending ratio necessary for stable operation by comprehensively assessing the results of a high-
temperature electric characteristics test method coupled with evaluation of plant operating performance.

Table 5.2: Typical Mn ore and sinter compositions confirmed

<table>
<thead>
<tr>
<th></th>
<th>Mn ore (%)</th>
<th>Sinter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>49.5 (34)</td>
<td>56.6 (38.6)</td>
</tr>
<tr>
<td>MnO₂</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Mn₃O₄</td>
<td></td>
<td>78.6</td>
</tr>
<tr>
<td>Fe</td>
<td>1</td>
<td>1.4</td>
</tr>
<tr>
<td>SiO₂</td>
<td>9</td>
<td>10.7</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.1</td>
<td>1.4</td>
</tr>
<tr>
<td>CaO</td>
<td>1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

5.1.4 Accountability on production unit

The plants producing SiMn/FeMn were always having certain metallurgical parameters to observe, which could be represented in the following manner:

Table 5.3: General metallurgical parameters observed

<table>
<thead>
<tr>
<th>Metallurgical parameter</th>
<th>Units</th>
<th>Details/Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average alloy composition</td>
<td>(%Mn, Fe, Si, C)</td>
<td>Covered in section 3.4</td>
</tr>
<tr>
<td>Average slag composition</td>
<td>(%MnO)</td>
<td>25.1 – 28.4</td>
</tr>
<tr>
<td>Mn metal recovered</td>
<td>(%)</td>
<td>SiMn (66.2); HCFeMn (78.3)</td>
</tr>
<tr>
<td>Mn:Fe ratio</td>
<td></td>
<td>5.4 – 7.6</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>kWh/tonne</td>
<td></td>
</tr>
<tr>
<td>Electrode consumption</td>
<td>kg/MWh</td>
<td>9.1</td>
</tr>
</tbody>
</table>

5.1.5 Confidence about technological-knowhow

The technological knowhow was demonstrated on how the installed technology was managed from the nature of the submerged arc furnace (SAF) i.e. if it is closed, semi-open or open, together with the installed electricity supply in MVA. For example, at plant P1 with the closed SAF, high-purity Mn₃O₄ could be prepared from low-grade rhodochrosite (MnCO₃) ore (LGRO). The Mn recovery efficiency was more than 97% with the blended precipitant of Na₂CO₃ and NH₄HCO₃ (1:1 mol. mol⁻¹). The total Mn content (TMC) of product increased with increase of decomposition time and temperature. The quantitative relationship between TMC and decomposition time as well as decompositions temperature could be fitted by empirical formulae.

When decomposing MnCO₃ at 1323 K for 120 min, the TMC of Mn₃O₄ could reach 72.01%, which was larger than that of the premium grade of mangano-manganic oxide for preparing soft magnetic ferrites. The product was investigated by (X-ray
Diffraction (XRD), Fourier Transform Infrared (FTIR) spectroscopy, and Scanned Electron Microscope (SEM). SEM images revealed that the product consisted of small and uniform particles with smooth surface and good dispersion.

Through XRD, FTIR and determination of TMC, the as-prepared product was confirmed to be high-purity $\gamma$-Mn$_3$O$_4$. The ionic distributions were formulated as $[\text{Mn}^{2+}]_2[\text{Mn}^{2+}_{0.3024}\text{Mn}^{3+}_{0.2937}\text{Mn}^{4+}_{0.3786}\Box_{0.0254}]_2\text{O}_4$. Below in Figure 5.1 depicts the slag phase of this observation at P1. And the same was also observed at S3 with the production of HCFeMn. The solid spheres are the metal oxides transforming from Mn$_3$O to MnO.

![Figure 5.1: Slag structure of a high MnO slag with solid MnO spheres in coexistence with a liquid phase](image)

The production process was able to focus on the important metallurgical variables that were monitored by the plant engineer. Table 5.3 illustrates the important metallurgical parameters that require benchmarking especially when managing the effects of input efficiencies.

<table>
<thead>
<tr>
<th>Metallurgical Parameters</th>
<th>Plant</th>
<th>P1</th>
<th>P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average furnace load (MW)</td>
<td></td>
<td>40.0</td>
<td>19.8</td>
</tr>
<tr>
<td>Operating time (%)</td>
<td></td>
<td>98.6</td>
<td>98.0</td>
</tr>
<tr>
<td>Productivity (tonnes/day)</td>
<td></td>
<td>1694.4</td>
<td>530.1</td>
</tr>
<tr>
<td>Power consumption (kWh/t)</td>
<td></td>
<td>5086</td>
<td>2677</td>
</tr>
<tr>
<td>Annual production (t)</td>
<td></td>
<td>600,000</td>
<td>180,000</td>
</tr>
<tr>
<td>Mn recovered (%)</td>
<td></td>
<td>78.6</td>
<td>68.1</td>
</tr>
</tbody>
</table>
5.2 Ferromanganese production functions

5.2.1 The SiMn/FeMn production function

The strictly general point of reference would be to describe the actual possible combinations of inputs and outputs. If this set is called \( T \), then \( T \) can be defined as:

\[
T(x, y) = \{(x, y) : x \text{ can produce } y \} \quad (1)
\]

in which \( T \) is the technology set, \( x \) is the amount of input and \( y \) is the amount of output. In this strictly general formulation, both \( x \) and \( y \) could be scalars or vectors. However, for now, both \( x \) and \( y \) should be considered as scalars (one input-combination and one output). The study did not consider each input for the single output of SiMn or FeMn but an input-combination for the SiMn or FeMn. The input combination is the Mn ore-carbon reductant-fluxes unit; and the furnace size and electricity used is considered a constant since it is also related to the furnace size, and thus the output size. The technology set \( T \) illustrates all the possible combinations of input and output. However, the ferromanganese production technology can also be defined in another way, i.e. as the input set \( X(y) \) which is defined as:

\[
X(y) = \{ x : x \text{ can produce } y \} \quad (2)
\]

But equation (2) will not be applicable to the research since the study does not consider the effect of each input element i.e. Mn ore or carbon reductant or fluxes but looks at a combination of inputs. But the study considers the input elements as a single unit to produce silicomanganese or ferromanganese. As mentioned previously, the ideal size of Mn ore feed for furnace is 3mm to 70mm with +4-5 to -10mm and +50 to -70mm size fraction not to exceed 15%. Similarly, size of coke should also be controlled. Different fractions of coke not only affect the porosity of charge but also affect the position of electrode inside the charge, resistance of charge, and the resultant heat distribution inside the furnace. Proportions of breeze coke (5mm to 10mm) and nut coke (10mm to 25mm size) should be properly controlled so as to promote favourable furnace condition. Hence proper screening of ores before charging was of paramount importance. And it will improve the furnace performance, and hence the overall FeMn/SiMn process performance. For example from equation (1) and case studies P1, P2, S1, S2 and S3:

\[
T((x)1375kg \text{ Mn ore} - 1,800t \text{ coke}, (y)1t \text{ Mn metal}) \leftrightarrow (which \ implies) \{(x)(1375kg \text{ Mn ore} - 1,800t \text{ coke}, (y)1t \text{ Mn metal}) : (x)(1375kg \text{ Mn ore} - 1,800t \text{ coke}) \text{ can produce } (y)1t \text{ Mn metal}\}.
\]
5.2.2 Optimal configuration of input materials

The Mn ore composition and characteristics is known before being delivered to the plant. Hence the plant engineer has an opportunity to assess the mixture of Mn ore required for optimal Mn recovery. This was a practice at P2 which uses carbonaceous silicate Mn ore primarily i.e. rhodochrosite and rhodonite, but also added 5% of Mn ore feedstock from the oxide Mn ore i.e. pyrolusite. The local manganese ores are low and medium grades with Mn/Fe ratio ranges between 3.0 and 5.5. Manganese to iron ratio is very important in the SiMn/FeMn production process. Mn/Fe weight ratio of 7.5 is required for production of standard ferromanganese alloy i.e. HCFeMn with 78 % Mn. Furthermore, the local manganese ores vary widely in their content of manganese, iron, silicon, alumina, lime, magnesia, potassium and sodium oxides, barium oxide and phosphorus. Mixtures of two Mn ores are usually used to be blend with Mn sinter. The charged Mn ores mixture amounts to 890 - 1890 kg per tonne produced alloy, averaging 1375 kg/ton, with Mn/Fe ratio ranging between 3.3 and 5.5, average 4.08

Coke is in short supply in South Africa; hence 70-80% of the carbon required for the reduction of the ore at P1 for HCFeMn is supplied in the form of coal. As these are closed furnaces, the volatiles from the coal were not burnt above the burden and leave the furnaces in the off gas. This volatile matter was scrubbed out in the wet scrubbers and was entrained and dissolved in the scrubber effluent. The scrubber effluent was then pumped into sealed settling dams where the solids and entrained organics settled out. The supernatant liquid containing the dissolved organics mainly in the form of phenols was returned to the scrubbers. A consequence of this closed circuit operation was that the concentration of phenols built to values in excess of 1500ppm, which are above the legislated value of 5 ppm. Some of the gas was used to produce 20MVA of electricity at P1, and a new process configured to eliminate the environmental shortcomings that could be faced. Given the analysis of the production function and the configuration of input materials, the following data was also recorded with the SiMn/FeMn average price of R14,000/t.

Table 5.5: Collected data of SiMn/FeMn plants’ costs

<table>
<thead>
<tr>
<th></th>
<th>Cost per tonne produced (R/t)</th>
<th>Annual production (kt)</th>
<th>Average annual revenue (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>1130</td>
<td>610</td>
<td>854 000 000</td>
</tr>
<tr>
<td>P2</td>
<td>834</td>
<td>180</td>
<td>252 000 000</td>
</tr>
<tr>
<td>S1</td>
<td>972</td>
<td>350</td>
<td>490 000 000</td>
</tr>
<tr>
<td>S2</td>
<td>985</td>
<td>250</td>
<td>350 000 000</td>
</tr>
<tr>
<td>S3</td>
<td>1052</td>
<td>400</td>
<td>560 000 000</td>
</tr>
</tbody>
</table>
From Table 5.5 above it was possible to derive a capacity-based cost curve for the manganese ferroalloys cases that were investigated. It is capacity-based because the study considered the input materials to be variable, and the various output capacities were the plant production targets to be achieved.

![SiMn/FeMn Capacity-based Cost Curves](image)

**Figure 5.2: Production capacity-based SiMn/FeMn cost curves**

From Figure 5.2, P1 is the most productive as compared to S3, and to a lesser extent S1 and S2. It is so because their production costs per tonne are almost similar i.e. they can all be rounded off to R1,000/t. P2 had their production techniques well suited for long term technical sustainability because it had higher input costs of electricity due to more quartz that needs to be added. The trend would be positively reversed by better blending of Mn ore by P2 to not only rely on the carbonaceous silicate Mn ores.
5.3 Areas of future focus

5.3.1 Technology improvements: Low grade ores

The reality is that some of the South African high-grade ores are getting depleted. Hence alternative treatment procedures of low-grade ores are required. At P2 the low-grade ores lead to the high usage of quartz, and thus leading to high electricity costs. But it was also clear that P2 did not use high quality reductant like the one with specifications as in Table 2.2.

5.3.2 Process control

Centralised versus decentralised monitoring of furnaces will become a more pronounced area in managing the comparability of the SiMn/FeMn product. At P1 there was centralization and at P2 the automated monitoring was decentralised with four control rooms. Importantly, it will be important for the plant processes to determine the percentage tolerances required between the various furnaces to satisfy the end-user processes like in steelmaking.

5.3.3 Mineralogical applications

The basic theory for production of manganese ferroalloys has already been described. The higher oxides of manganese which are present in Mn ore such as MnO₂, Mn₂O₃ and Mn₃O₄ are unstable at higher temperature and decompose in presence of carbon and carbon monoxide. MnO, dissociates to Mn₂O₃ at temperature of 430°C. Mineralogy and the techniques in mineral/phase analysis are being applied in a wide variety of pyrometallurgical investigations, where they assist in process design, problem-solving, and model validation. The study observed other areas of importance in pyrometallurgy for refocusing the current study:

- The performance of FeTiO₃ (ilmenite) as an oxygen carrier in chemical-looping combustion. The phase chemistry of the Fe-Ti-O system shows that FeTi₂O₅ (pseudobrookite) and TiO₂ (rutile) are formed in oxidation; that subsequent reduction forms either FeTiO₃ (ilmenite) or Fe₂TiO₄ (ulvöspinel), depending on whether the TiO₂ (rutile) formed takes part in further reaction or not. Identifying phases, their compositions and morphologies by means of XRD, SEM and EDS will confirm which course the redox reactions follow, and in turn answer questions about the performance and potential of ilmenite as an oxygen carrier.
- Problems related to the phase-chemical composition of furnace feed to the smelters can be alleviated by blending according to concentrate composition
and mineralogy.

- Difficulties encountered in the processing of furnace and converter mattes may be avoided by careful control of matte composition and monitoring of the mineralogy of the ore.
- The losses of Mn metal to furnace slag have been characterised, and it has been established that the current modelling practices must be validated by mineralogical analysis.

From a mineralogical understanding and characterisation as observed and shown in Figure 5.2 below, the behaviour of Mn metal at various temperatures like at 1000°C and 1200°C below, should be known for maximum metal recovery. The maximum recovery could be yielded at a specific temperature correlating with the specific mineralogical properties of Mn ore. This factor has to be infused more to reliably design the SiMn/FeMn plant processes, particularly the temperature control at various process points. Higher temperatures are known to provide better yields of Mn metal, but it remains a general assessment.

Once more from equation (1):

$$T((x)1375 \text{ kg Mn ore} - 1,800 \text{t coke}, (y)1 \text{t Mn metal}) \leftrightarrow \{(x)(1375 \text{ kg Mn ore} - 1,800 \text{t coke}, (y)1 \text{t Mn metal}) : (x)(1375 \text{ kg Mn ore} - 1,800 \text{t coke}) \text{ can produce } (y)1 \text{t Mn metal}\}.$$

In terms of the Mn metal contraction at various temperatures, it would also be important to understand at plant process level for benchmarking; the relationship between Mn metal contraction (from Figure 5.2) and the Mn metal yields (from the equation above).

![Figure 5.2: Typical contraction of Mn ore between 1000°C to 1200°C](image)
5.3.4 Alternative production methods

The basic theory for production of FeMn is already described. The higher oxides of manganese which are present in Mn ore such as MnO₂, Mn₂O₃ and Mn₃O₄ are unstable at higher temperature and decompose in the presence of carbon and carbon monoxide. MnO₃ dissociates to Mn₂O₃ at temperature of 430°C. Hence it was also found that the existence of carbonates in the Mn ore are a determinant factor of the rate of reduction of the Mn ore.

5.3.4.1 Submerged Arc Furnace versus DC Arc Furnace

When an AC submerged-arc furnace is to be scaled up, the electrodes need to be made bigger as Söderberg electrodes have a limit on current-carrying capacity and the risk of electrode breakages is increased significantly when this current-carrying capacity is exceeded. Furthermore with scale-up, the furnace resistance decreases with increasing electrode diameter. In addition, the magnetic inductance or reactance of a furnace typically increases with electrode size. Larger electrodes therefore have a compounding effect on the furnace power factor i.e. the ratio between the resistance and the reactance of the furnace electrical circuit.

With the power factor above certain threshold, there will be no major operational difficulties, but at certain thresholds, a phenomenon called the interaction effect becomes significant and creates continual operational control problems. In short, the problem of the interaction effect in a three-phase AC current electric arc furnace relates to the phenomenon that a control change made to one electrode also affects the electrical parameters in the other two electrodes to a certain degree. Such a control change may include slipping an electrode, raising or lowering of the electrode, or changing the control setpoint for current, or tapping the furnace load up or down.

In effect, this interaction effect phenomenon may result in an almost unmanageable furnace from a control perspective when the power factor drops below 0.5. The patent by Barcza et al claims that a DC submerged arc furnace could be scaled up without being limited by the control problems associated with the interaction effect, as the current would flow through the hearth and then there would be no current interaction. It is further believed that even with a graphite electrode as anode, the control in a multi-electrode scaled-up DC furnace need not necessarily be a problem, regardless of the current “interaction” between cathodes and anode(s)]. Since electromagnetic inductance creates reactance only with alternating current, a further
benefit of a multi-cathode large-scale DC furnace would be the fact that there would be no reactance in the electric circuit(s), with associated benefits in terms of greater power generating capacity.

5.3.4.2 Submerged Arc Furnace (SAF) versus Blast Furnace (BF) process
High carbon ferromanganese is produced entirely through submerged arc furnace route. This route has the greatest disadvantage of high electrical energy consumption. The producers of ferroalloys are facing difficulties to stay competitive due to the increasing tariff of electric power. HCFeMn can potentially be produced in blast furnaces much more economically compared to submerged arc furnaces with co-generation of electric power using the blast furnace off-gas. Some modifications will be required in the design of conventional blast furnaces for producing ferromanganese. For example, Tana Kotf mini blast furnaces can be conveniently used for the manufacture of FeMn, since most of these modifications at furnace top equipment have already been incorporated in the design of these furnaces.

The BF process offers specific advantages under South African conditions since it does not consume electric energy as the main fuel and therefore, has no uncertainty in operations. It is rather possible to generate electricity from the blast furnace off-gas. Overall cost of production is low. Mn metal yield is also higher compared to SAF route. However, no ferroalloy other than FeMn can be manufactured in the blast furnace. The reductant usage rate is higher as compared to the SAF route, since the reductant replaces the electric energy consumption as applicable for the SAF route. Therefore, the advantages of the process are the following:
- High Mn metal yield
- Low cost of production
- Produces electric energy

Comparing the submerged arc furnace (SAF) and the blast furnace (BF) yielded the following observations:
(a) Production of Fe-Mn through BF route was environmentally friendly and techno-economically feasible;
(b) Blast furnace design with suitable modifications in furnace top equipment shall be adequate for production;
(c) Product through BF route would always remain competitive due to 35% lower cost of production compared to SAF route; and
(d) In the BF process a lot of metal is lost as fines as part of the slag and dust.
5.3.4.3 Billeting versus granulation

Granulated SiMn/FeMn product can be produced through the GRANSHOT process as in the production of ferronickel granules to save storage space, to eliminate the fines and for better ferroalloy product quality. Previously in the steel industry, granulation was compared to alternative melting stock material supplied in the form of ingots and premixed material i.e. mix of pure iron and alloys used for investment casting purposes. Melting experiments were carried out in a 100kg high frequency furnace for two standard steel grades. Investigated parameters were melting times, material handling properties, chemical analysis accuracy and liquidus temperature.

The granulation principle is based on a heat exchange between the liquid metal and cooling water. There are no fundamental variations in the process whatever type of metal to be cast. The liquid metal stream, would be poured from a tundish or ladle, strikes the refractory sprayhead placed in the centre of the granulation tank. The sprayhead splits up the metal stream into droplets/granules that are distributed evenly over the granulation tank water surface. The melting tests showed that the GRANSHOT material melted considerably faster compared to ingots and premix material. Another great advantage when using the GRANSHOT granules was found to be the possibility to obtain very exact charges. These can be within a few grams of deviation when charging a furnace. Size distribution of the GRANSHOT material also made them convenient to handle. The same characterisation can be extended to manganese ferroalloys. When it comes to analysis accuracy both granules and ingot heats were well within the analysis boundaries for the product grades, while none of the premixed heats fulfilled the chemical analysis specification completely.

Using a premixed raw material therefore requires thorough analysis control and possible adjustments in order to meet the target composition. This means extra work for the investment caster as well as increased process time, analysis costs and power consumption. The results from the liquidus temperatures measurements showed the advantage of using a raw material with high analysis accuracy in order for the caster to have a reliable value of the liquidus temperature. The results also showed the importance for casters to demand narrow composition ranges from melt stock suppliers, to ensure good quality during casting, especially for high alloy material.
5.3.5 Power generation

5.3.5.1 Thermal coal usage

At Plant S1, non-metallurgical coal is used to generate electricity to melt Mn ore in the shaft-type smelting furnace. A power generation plant could be installed enough to produce generation capacity for the melting process. It will eliminate any reliance on the electricity from the public grid system. Small steam boilers could be effected, and if possible excess power could be sold back into the power grid. Most of the process designs being considered for development with some patented, are for the potential heat wastage to be reversed to effect pre-reduction processes, and drying processes. The process is effected through the lowest reducing agent rate achieved through high-pressure blast by hot-blast stove and gas distribution control by bell-less type charging equipment.

In this approach, the technology being applied uses small coke by high-pressure operation. The smelting technology adjusts the hot metal components from tap to tap. Introduction of computer-controlled integrated electrical instrumentation. At Plant S1, the production capacity is 158,000tpa (or 450tpd), producing LCFeMn and MCFeMn at the following parameters:

- Blast air input: 700N m$^3$/min
- Oil injection: 71kl/day
- Blast temperature: 1200°C
- Inner volume: 450 m$^3$

5.3.5.2 Flue gases heating from SiMn/FeMn process

During the production of ferro alloys in electric smelting furnace lot of heat energy is wasted through flue gases which is being discharged to the atmosphere at a temperature as high as 500-900°C. Gas evolved in the operation is 700 to 1000 NM$^3$/tonne of alloy. The figure varies with the type of alloy produced. Therefore a rich fuel gas with a calorific value of 2000-2500 KCal/M$^3$ is evolved from a ferro alloy furnace that is being wasted to atmosphere. If heat evolved is utilised economically for drying of wet charge, steam generation or pre-reduction energy saving can be achieved. Heat balance calculations can assist in identifying the process where heat losses occur. From the above heat balance it was found that metal, slag and gas carried lot of heat energy. Moreover heat taken away by circulating water is as high as 22% of total energy input. Efforts should be made so that heat losses are reduced or heat wastages are reversed.
At some of the ferroalloy plants in Japan preheating and pre-reduction of charge is being practised. Flue gas temperature of closed electric smelting furnace for production of FeMn is around 500°C. For 9 MVA furnaces about 35,000 NM³/day of gas passes to the atmosphere. Hence lot of heat energy is wasted to the atmosphere. Calorific value of the gas is around 1900 KCaI/M³. Attempt has been made for utilisation of flue gas for preheating of charge by increasing pressure under furnace cover and flue gas is allowed to pass through shaft carrying the charge. In shaft preheating is done by counter current heating of the charge by combustion of clean furnace gas. As in the case of FeMn production preheating and pre-reduction takes place at the upper layer of smelting furnace charge, less benefit is derived. Most losses can also be reduced by reducing flue gas temperature by increasing the charge height. In such case flue gas has to pass through greater column of charge which will transfer sensible heat to the charge for achieving this furnace design has to be modified suitably.

5.3.5.3 Cooling heat from casting

The casting process produces a fair amount of heat that can be used for drying the feedstock in a form of Mn ore and reductant (and fluxes). Moisture content in charge affects furnace condition very adversely. Increased moisture content in the charge not only takes more power for evaporation of moisture but also increases power due to poor furnace operating condition. With the increase in moisture screenability of charge is reduced, due to blockage of screen opening. Hence fines pass through along with charges in the furnace without being screened. These fines carry more moisture than lumpy ore. Hence porosity of charge reduces, resulting in crust and bridge formation inside the furnace. This affects uniform descend of the charge, uniform passage of flue gas and heat distribution inside the furnace.

The moisture content in coke varies widely. Hence carbon balance in the burden can be disturbed. If burden is disturbed it affects the slag composition thereby the melting point. Hence due to variation in moisture, the furnace operation is also affected. Increase in 1kg of moisture increases power by 1Kwh approximately. Further there is increase in power due to dissociation of water in presence of carbon leading to endothermic reaction. There will be further increase in power consumption due to adverse furnace condition. Hence moisture content in the charge should be controlled. Coke absorbs around 15% maximum moisture. If the same is dried before charging in furnace not only the moisture content in furnace is reduced but the burden control can be properly exercised. Apart from water content in charge water
due to leakage inside the furnace should also be checked in order to control increase in power consumption. Hence all precautions should be taken to avoid water leakage inside furnace, and heat from casting operations can be used to dry the charge.

5.4  Manganese ferroalloys production paradigms

5.4.1 Adoption criteria
The most important aspects identified are the following:
(1) Firmed-up production capacity, (2) Optimal configuration of input materials, (3) Potential operational savings, (4) Accountability on production unit, and (5) Confidence about technological-knowhow.

![Production cost representation](image)

Figure 5.3: Production function radial representation

A fair representation of the aspects in terms of the FeMn/SiMn production process can be represented as follows from Figure 5.3 and Table 5.1. A count of 1 is the worst and 10 the best attribute to the production process of manganese production process.

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Critical details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production context</td>
<td>KPIs and efficiency measures – 6</td>
</tr>
<tr>
<td>Input materials configuration</td>
<td>Materials blending and preparation and measures - 9</td>
</tr>
<tr>
<td>Potential operational savings</td>
<td>Installed technologies and production platforms - 7</td>
</tr>
<tr>
<td>Production unit accountability</td>
<td>Metallurgical parameters management and measures - 8</td>
</tr>
<tr>
<td>Technology know-how</td>
<td>Metallurgical parameters management and stoichiometry - 6</td>
</tr>
</tbody>
</table>
### 5.4.2 Conclusive plant production standards

From Figure 5.3 it was clear that the annual production that has to be achieved is important. The input efficiencies have to be worked after a production target has been set. Hence all the elements in Table 5.6 that has a meaningful bearing on the attainment of the annual targets as per the specific production capacities of the plants.

From Table 5.6 above, a representation of scores could be made emphasising the most important elements for the five case studies. This is represented as Figure 5.4 below.

![Production aspects ranking](image)

**Figure 5.4: Representation of identified production aspects with respect to production capacities**

All the plants had a dependency on the input materials, as the most important technical aspect to be considered. And it further confirms the furnace operations as the limiting processes in the plant processes. The Mn ore and reductant blending, sizing and general preparation are the most critical aspect. Other observations have also pointed to the same conclusion. The least important aspects were the production context and the technology know-how. With the adoption of other techniques employed in the other ferroalloys plants, the least important aspects can make the plants have a dependency on them e.g. if granulation is adopted and/or production follows the blast furnace or DC furnace routes.

A potential for operational savings as measured in R/t is also important particularly when the commodity cycle is low, and should always receive consideration as a factor of production. Hence overall, the input efficiencies cannot be ignored.
5.5 Conclusion

5.5.1 Choice between efficiency measures

The question arises as to which of the many possible benchmarking techniques and/or efficiency measures to select when we want to measure the performance of FeMn/SiMn production processes. There are several applied and theoretical aspects to consider. One very important aspect is controllability. The inputs and outputs that can be controlled by the entities to be evaluated are important as it is generally not very informative or motivating to be judged on the basis of factors that cannot be controlled. Therefore, the choice between input- and output-based evaluations, between general evaluations or conditional evaluations where some factors are fixed, and between allocative and technical efficiency depended very much on controllability.

It follows from the controllability perspective that the time perspective is relevant because, in the long run, more factors are usually variable. The level in a hierarchy that is evaluated is relevant. A plant process may, for example, be evaluated based on Mn ore technical efficiency or reductant technical efficiency, whilst a plant engineer who is responsible for resource procurement and allocation may be more correctly evaluated based on allocative efficiency or, if prices are not available, using structural efficiency measures. A production plant may not have much control over the ore composition, and as a result, input-based evaluations may be more relevant as it was followed in this study.

More generally, the intended use of the efficiency score is crucial. In a learning experience, the exact efficiency measurement are less important than the ability to find relevant comparative plant processes, taking into account the plant’s own preferences, strategies, and objectives. The directional distance function approach may be particularly useful in this case due to its flexibility. In an allocation application, the distinction between fixed and variable inputs and outputs are often important, which might lead a FeMn/SiMn plant to favour a Farrell approach, with some inputs and outputs that are non-discretionary, or even to opt for a directional distance function approach. In an incentive application, the task is to find an aggregation of performance that allows optimal contracting.
The incentive rationales for radial measures such as the Farrell approach could be provided. On a very specific level, ease of interpretation is also important. One of the advantages of the Farrell measure in applications is that it is very easy to interpret. One can create many more or less ingenious ranking systems, and those SiMn/FeMn plant processes that do not perform well may have strong objections as to how the ranking was constructed and how the different performance dimensions were aggregated and weighted. One important property of the Farrell measure, however, is that it does not directly weigh the various dimensions. If a plant is not performing well according to this measure, it is very difficult for that plant to explain away the results because it is underperforming in all areas rather than in only one potentially overrated dimension. This is because the Farrell measure uses proportional improvements. This argument can actually be given a game theoretical formalisation.

As a last practical concern, data availability and ease of computations can be mentioned. The more we know about the values, that is, component costs and process prioritisations, the more focused the evaluations could become. Costs for inputs, for example, enable plants to conduct cost efficiency analyses that decompose efficiency into allocative and technical efficiency, which would provide more information than would a pure technical efficiency analysis. Likewise, using data from several years allows more robust evaluations and may possibly allow plants to separately consider general productivity shifts and catch-up effects. Additionally, in more advanced applications involving, for example, complicated structural and network models, computational issues could be considered.

5.5.2 SiMn/FeMn production process measure
It was less motivating to conceptualise complicated calculations if they were difficult to implement because the resulting programmes would become too non-linear. It was also important to keep the rational ideal model in mind when considering indices of technical efficiency. Ideally, efficiency should reflect utility effectiveness or process parameters effectiveness. We know that dominance relationships were maintained under utility effectiveness in that if one plant process dominated or was better than the other, it was more utility effective. It cannot, however, be ascertained that inefficient plants were less utility effective than the efficient ones. Therefore, although efficiency provided a useful filter, efficiency was not a sufficient condition for plant process effectiveness, and there should no fixation on the ability to make efficiency evaluations based on a minimum of assumptions.
However, it was still important to think of ways to elicit preferences and make evaluations that more closely captured the required preferences. After all, small improvements of the right type may be more valuable than large improvements to less important aspects. A general problem of measuring the performance of a FeMn/SiMn plant by gauging it with the plant technology was closely examined. There was a definition of efficiency using the least resources to produce the larger tonnages, and have looked at different ways to measure efficiency levels. Most widely used measures were covered i.e. the Farrell efficiency measure, focusing on proportional improvements to inputs or outputs, and have highlighted the alternative approaches such as directional distance functions with excess, an additive measure of the number of times a given improvement bundle is feasible.

The study also observed how preference or price information allowed more informative evaluations, including decompositions spotlighting allocative and technical efficiency factors. It was shown how the FeMn/SiMn could distinguish between frontier shifts and catching up in a dynamic context as well as how structural efficiency could be evaluated by looking at variations of production processes. Lastly, we have discussed some key concerns related to the choice between alternative measures in arriving at the critical aspects of the benchmarking techniques of a smelting operation of SiMn/FeMn plant.
References


28. Howat, DD, 1982. *Factors Affecting the Production of Fines During the Screening and Handling of High-Carbon Ferromanganese*, MINTEK, RSA


