Developing an evaluation model for cost saving initiatives on sinter plants

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Abstract

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Keywords: Sinter plants, Steelmaking industry, Cost savings, Cost saving initiatives, Load shift, Evaluation matrices, Evaluation model.

Ever-rising operating costs are placing the South African steel industry under significant financial pressure. Energy costs are increasing at a rate higher than inflation which makes it extremely difficult for local steel producers to remain competitive in a market which is flooded by cheaper imported steel.

Energy cost savings initiatives such as improved efficiencies, load shifting and peak clip projects have already proved to reduce the operating costs of mines in South Africa. The implementation of similar energy cost savings projects in the steel industry can assist to alleviate the operating costs of steel plants. With their main focus on production, plant personnel seldom have the time and opportunity to concentrate on the reduction of energy costs.

Steelmaking is a complex process with several concurrent and integrated systems. Numerous studies focussed on the larger downstream energy consumers in the steel production process and very limited consideration has been given to the raw material preparation processes. Amongst the many raw material preparation processes, literature has indicated that the most significant energy cost savings opportunities exist on sinter plants.

The main objective of this study is to investigate the potential for energy cost savings opportunities on sinter plants in South Africa. Literature on existing energy savings opportunities were thoroughly investigated. An evaluation process was developed to identify those that are most feasible for the South African environment.

A specific South African sinter plant was selected as a case study. A list of all potential cost saving opportunities was compiled for evaluation against a set of predefined criteria as defined in the various evaluation matrices contained throughout this study. The evaluation matrices provided inputs to a defined initiative rating function and all potential alternatives were rated.

The most feasible cost saving opportunity was found to be the alignment of the sinter production schedule with that of the Eskom time-of-use (TOU) periods. Large fans driven by energy intensive electrical motors are used during the sintering process. A developed simulation indicated that it is possible to schedule production away from peak TOU periods thereby reducing the overall electricity cost.

Pilot studies were conducted to investigate the possibility of performing a load shift. An electrical consumption load shift between 9 MW and 14 MW was achieved during these studies. A load shift of 9 MW is equivalent to an annual cost saving of R10 million. The pilot studies therefore proved that electricity costs on sinter plants can be reduced by optimising production schedules.

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Table of contents

List of figures

List of tables

List of equations

Nomenclature

Symbol	Description	Unit of measure
°C	Measure of temperature	Degrees Celsius
t	Measure of mass	Tonne
G	Denotes 1×10^9	Giga
g	Measure of mass	Gram
M	Denotes 1×10^6	Mega
J	Measure of energy	Joule
m	Measure of distance	Metre
m^3	Measure of volume	Cubic Metre
k	Denotes 1×10^3	Kilo
W	Measure of power	Watt
Sm^3	Reference volume	Standard Cubic Metre
h	Measure of time	Hour
min	Measure of time	Minute
s	Measure of time	Second
d	Measure of time	Day
y	Measure of time	Year
a	Measure of time	Annum (yearly)

Abbreviations

Symbol	Description
BE	Barrier evaluation function
BF	Blast furnace
BFG	Blast furnace gas
BOF	Basic oxygen furnace
COG	Coke oven gas
DSM	Demand side management
FFS	Flame front speed
HTFS	Heat transfer front speed
IR	Initiative rating
KSC	Khouzestan Steel Company
LCD	Liquid crystal display
LS	Load shift
MP	Multiplier prioritisation function
MQI	Melt quantity index
ɳ	Efficiency
PC	Peak clip
PFD	Process flow diagram
PID	Proportional–integral–derivative
RDI	Reduction degradation index
R	South African Rand
RI	Reducibility index
SCADA	Supervisory Control and Data Acquisition
SSW	Segregated slit wires
TI	Tumbler index
TOU	Time-of-use
VSD	Variable speed drive

1. Introduction

This chapter provides background and highlights the relevance of the study.

1.1 Preamble

This chapter provides the background to and the importance of the study. The South African steel industry and steel production processes are discussed. The problem statement, study objectives, and scope are explained and act as the boundaries for this study.

1.2 Overview of South African steel industry

According to the World Steel Association, South Africa was the 24th ranked crude steel producer in the world during 2016 [1]. Figure 1 provides a breakdown of the largest steel producers with their crude steel production for 2016 in million tonnes. This clearly indicates that China dominated the steel production with nearly 50% of the total world steel production. South Africa had a total crude steel production of 6.1 million tonnes which almost seems to be negligible.

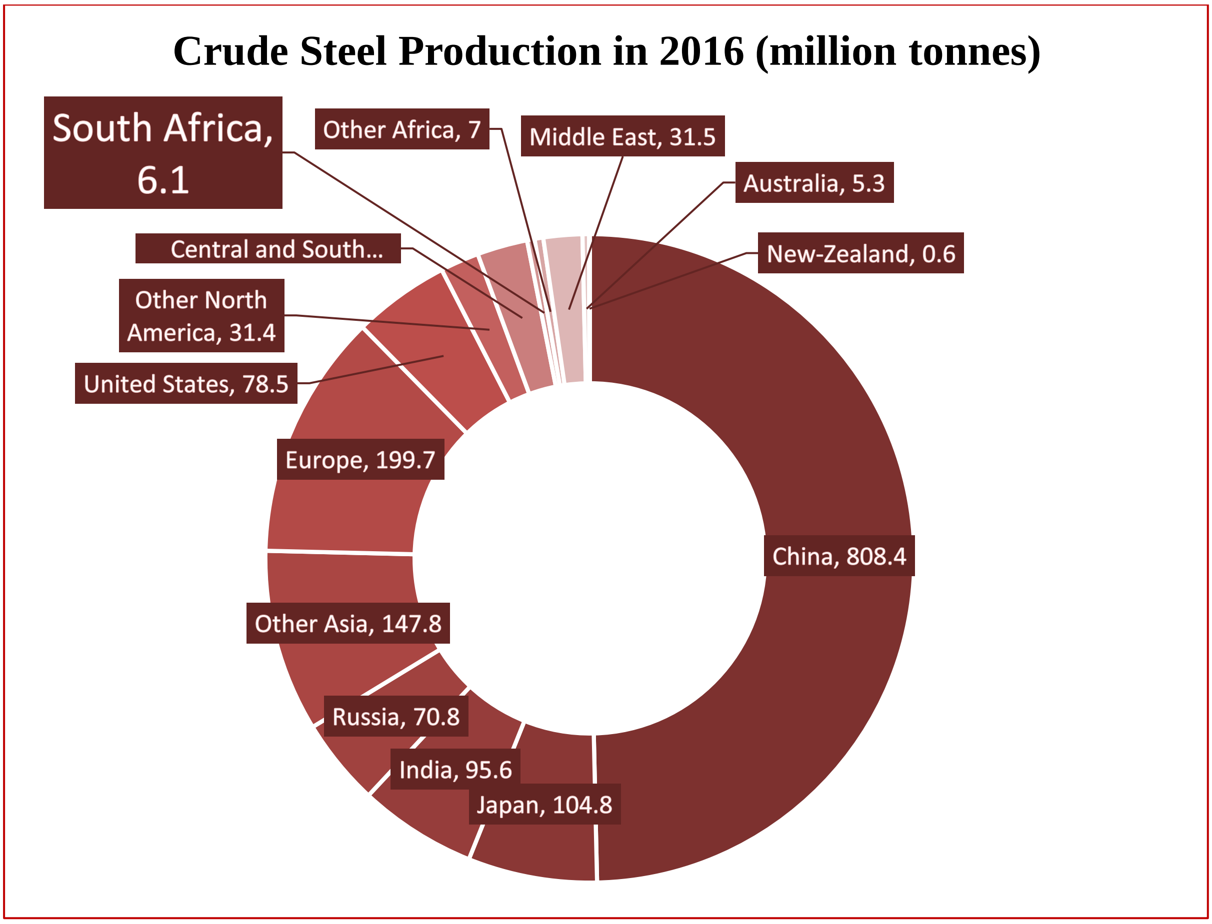

Figure 1: World crude steel production[1].

The steel industry in South Africa faces the same predicament as the rest of the world. With the rapid expansion of the Chinese steel sector since 2000 the global steel sector has been experiencing a state of overcapacity. The global steel sector has an increased capacity of 2300 million tonnes per annum, which is approximately 800 million tonnes higher than the global demand [2].

Financial incentives and subsidies offered by the Chinese government has encouraged the drive to increase capacity. The more steel produced by Chinese steel producers, the bigger the subsidies received from their government and the smaller the reliance on high market prices to remain profitable [2].

These subsidised Chinese steel imports flood the South African market as it is much cheaper to import than to buy locally produced steel. This places the local steel producers under significant pressure. Figure 2 clearly indicates an increase in the percentage of imported steel in recent years.

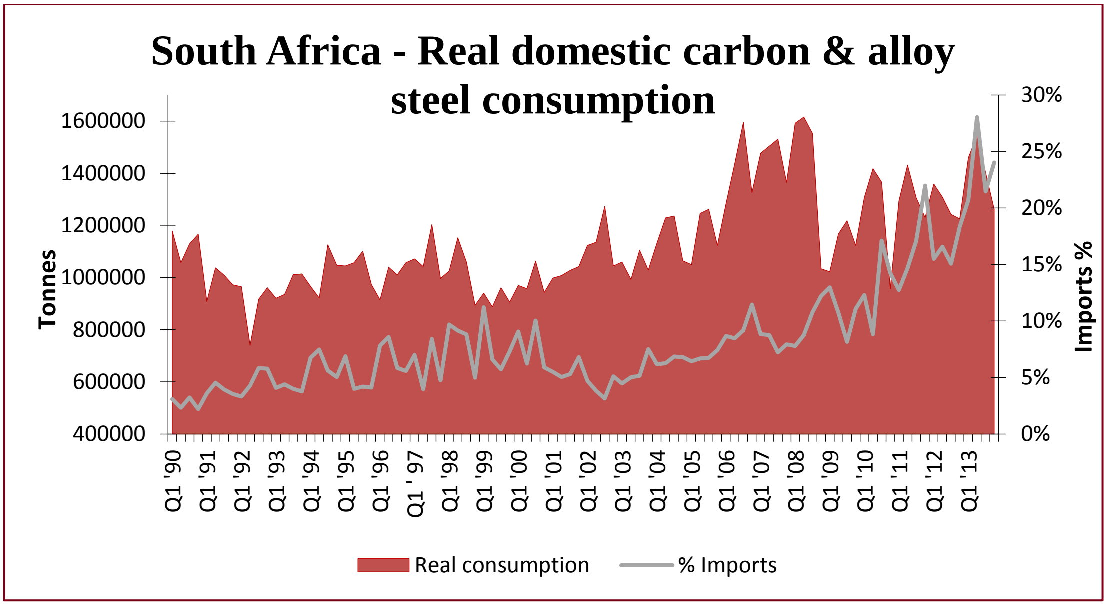

Figure 2: South African steel consumption and imports[1].

In 2015 the South African government stepped in and introduced a 10% import tariff on certain imported steel products. Unfortunately, this 10% import tariff charge is the maximum allowed by the World Trade Organisation [3]. Figure 3 visualises the dominant competitiveness of the imported Chinese steel.

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[1] "Real Steel Consumption," 2013. [Online]. Available: http://www.saisi.co.za/index.php/steel-stats/real-steel-consumption. [Accessed: 29-Jan-2017].

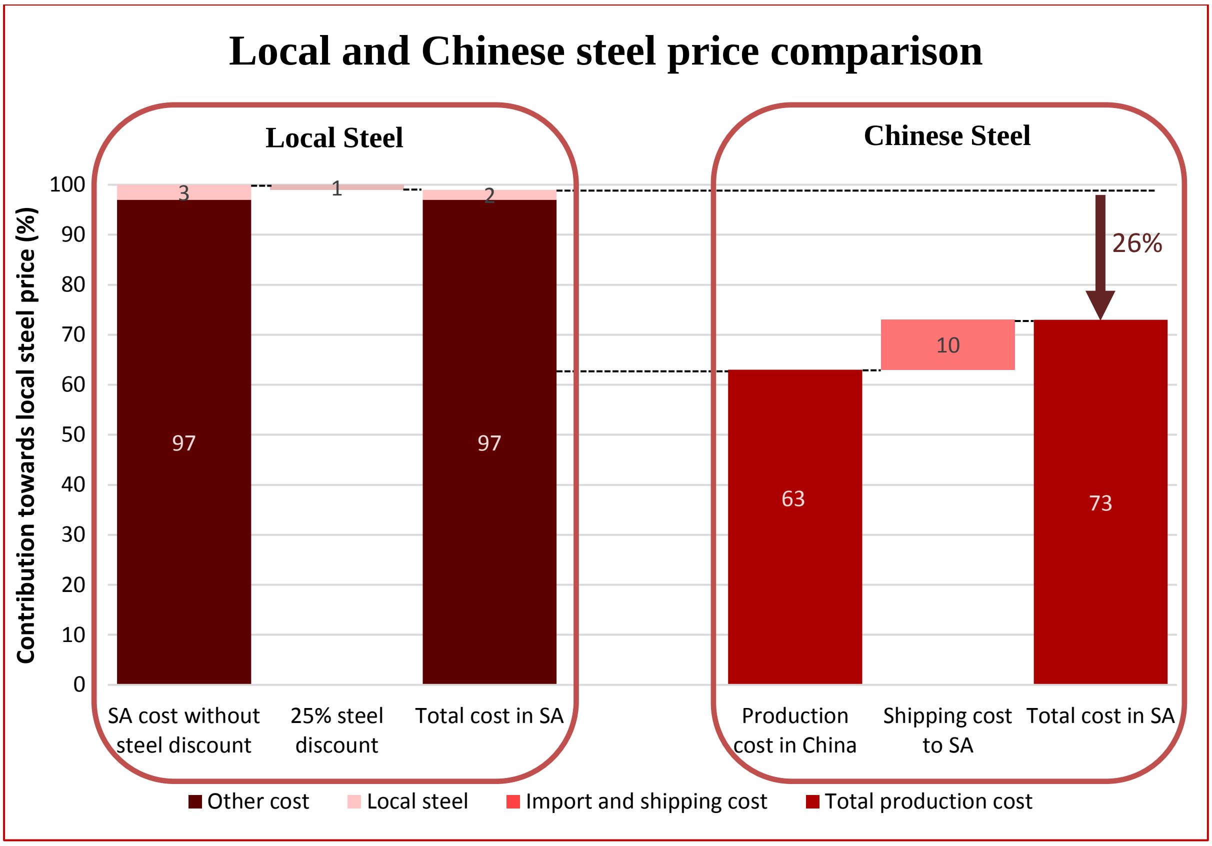

Figure 3: Local and Chinese steel price comparison [4].

As a counteract for the above-mentioned predicament all major world steel industries pursue continuous operational savings and other developments in the steel production processes to remain competitive. Worldwide energy consumption in steel production was reduced by 60% over the last 50 years [5].

Energy constitutes approximately 23% of the total steel production input costs according Figure 4 and it was also proven to be the best aspect to reduce input costs [5]. This makes energy the second largest cost input and will be the primary focus in this study to reduce production costs.

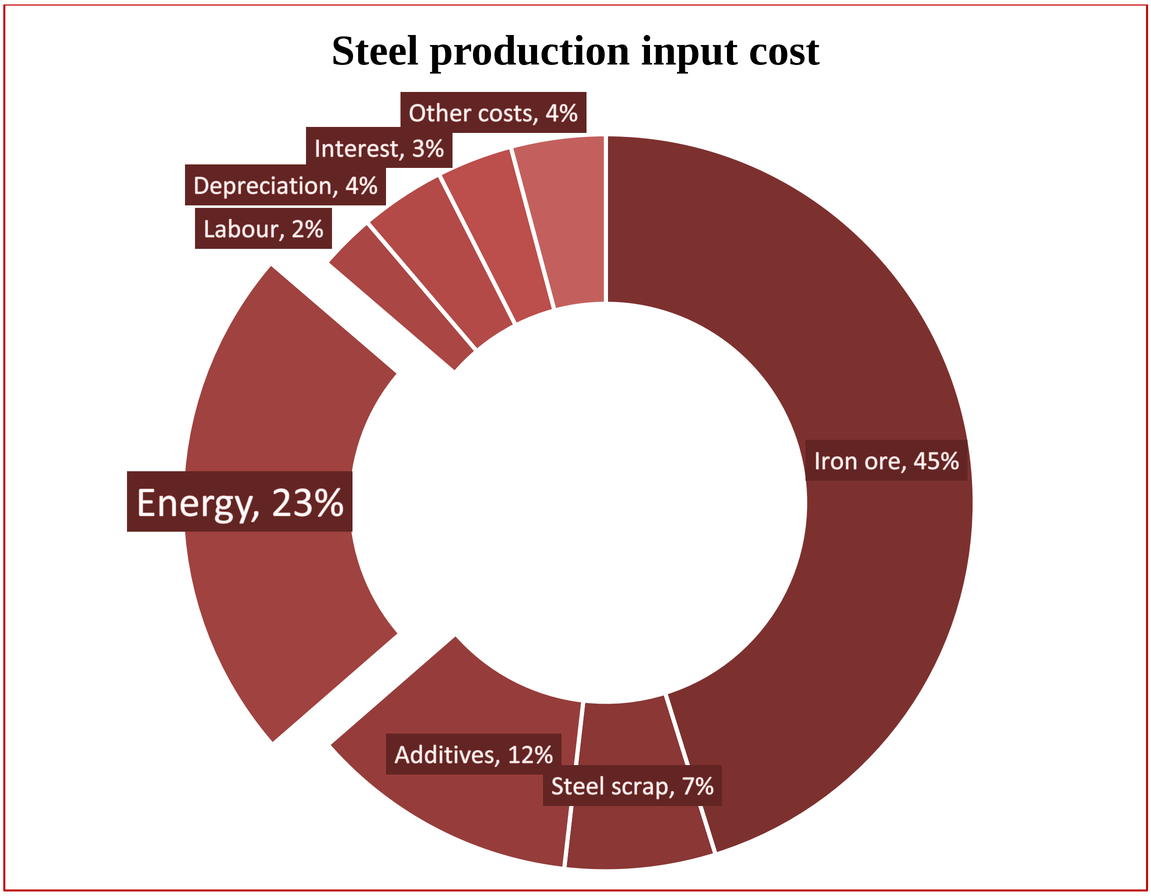

Figure 4: Steel production input costs[2]

Energy costs in South Africa, especially electricity costs since 2008, increased at a higher rate than inflation. In Figure 5, this major steel price driving force can be seen. The study will therefore mainly focus to investigate energy savings initiatives.

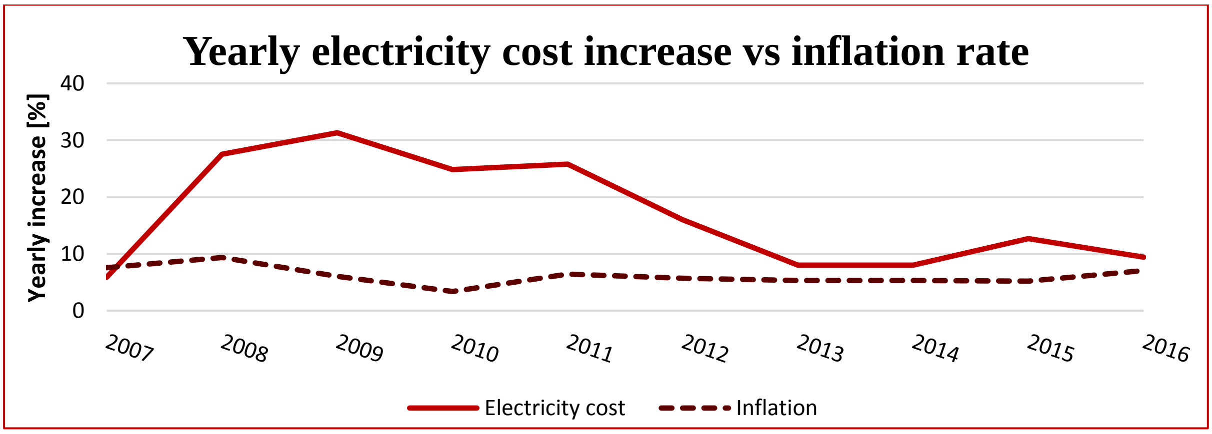

Figure 5: Yearly electricity cost increase [6] *vs inflation rate in South Africa*[3]

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[2] "Metal Miner," 2018. [Online]. Available: https://agmetalminer.com/steel-production-cost-model. [Accessed: 22-Feb-2018].

[3] "Worldwide Inflation Data," 2017. [Online]. Available: http://www.inflation.eu/inflation-rates/south-africa/historic-inflation/cpi-inflation-south-africa.aspx. [Accessed: 22-Feb-2018].

Studies also showed that not all the plants with low energy intensities are utilising the latest technology. Certain plants have proved that low energy intensities are possible with optimal operational knowledge and good operational systems [5].

1.3 Steel production process

1.3.1 Preface

The steel production process is an energy-intensive process where the chemical properties of the iron are altered to form steel. In 2013 the iron and steel production sector was responsible for 18% of the total world industry energy consumption. According to the International Energy Agency there is still potential for a 20% reduction in energy consumption in the iron and steel sector [7].

Coal, electricity and natural gas constitute to approximately 95% of the energy consumed by the iron and steel sector. The remaining 5% energy comes from energy sources such as biofuels, oil and heat[4]. Steel production is a complex process accomplished by several interrelated processes. The major processes in steel production are:

- Coke production;
- Sinter production;
- Iron production;
- Steel production; and
- Steel rolling and finishing [8].

Except for natural gas there are three alternative by-product gases used as gaseous fuels during the steel production process. These gases are coke oven gas (*COG*), blast furnace gas (*BFG*) and basic oxygen furnace gas. These gases are all by-products resulting from the different processes within steel production [7].

The following sections will provide a brief overview of each of the above-mentioned processes.

1.3.2 Coke production

Metallurgical coke is produced through the process of coal distillation. Coal distillation is done by heating coal in an oxygen-free atmosphere to remove most of the volatiles present in the coal. After most volatiles are removed almost the entire remaining mass is carbon known as coke. This metallurgical coke is used at the iron production process by reducing the iron ore to iron [8].

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[4] "Energy balance flows." International Energy Agency, 2014. [Online]. Available: http://www.iea.org/Sankey/index.html#?c=World&s=Final-consumption [Accessed: 29-Jan-2017].

COG is a by-product gas recovered during the coke production process. It has a heating value of approximately 17.5 MJ/m^3. It is typically used for power generation or for heating purposes during raw material preparation or in the reheating furnaces at the steel mills [7]. The coke production process consumes between 0.75-2 GJ of energy per tonne crude steel [9].

1.3.3 Sinter production

Sinter is fine iron ore, coke, anthracite and other additives melted together into clustered material of a suitable size to be charged into the blast furnace (*BF*). The raw materials are mixed together and spread across the sinter strand [8], [10]. The ignition hood located above the start of the sinter strand ignites the fine coke and anthracite particles in the mixture. The sinter production process consumes approximately 2-3 GJ of energy per tonne crude steel, which constitutes approximately 15% of the total energy required during the steel production process[9].

The ignition of the coke and anthracite cause surface melting and material clusters to form throughout the sinter strand. The sinter clusters are then crushed and screened before it is fed into the *BF* [8].

1.3.4 Iron production

Iron ore, sinter and fluxes are all layer-charged from the top of the *BF* [11], [12]. The *BF* consumes approximately 10-13 gigajoules of energy per tonne crude steel [9]. Iron ore is reduced and the liquid iron and slag descends to the bottom of the furnace where it is captured in the hearth of the furnace [11], [13].

In the furnace hearth, the slag floats on top of the denser liquid iron [14], [15]. Slag and liquid iron are separated and tapped from the *BF*. The liquid iron is tapped and transported to the steel plant for further processing [11].

Approximately 40% of the energy input from coal and coke into the *BF* is converted into *BFG* [16]. The *BFG* is typically used for power generation and at the blast furnace stoves, but it can also be used at the reheating furnaces and coke ovens [7].

1.3.5 Steel production

The *BF* /basic oxygen furnace(BOF) and the electric arc furnace are the most common steel processing methods [15], [17], [18]. Each processing method consumes approximately 1-1.5 GJ of electricity per tonne of crude steel [9].

Basic oxygen furnace

Liquid iron and steel scrap is added to the liquid iron in the basic oxygen furnace. A water-cooled lance injects oxygen at supersonic velocity into the liquid iron mixture. The oxygen reduces the carbon content in the liquid iron to less than 1% to form liquid steel. Additives are added to the steel to form desired alloys and specific steel grades [15], [19].

The basic oxygen furnace off-gas is the final by-product gas generated from the steel production process. It is a very dirty gas and therefore has very limited uses. It is mainly used for heating the coke at the coke ovens or for power generation [7].

Electric arc furnace

Electric arc furnaces are usually charged with steel scrap. Large quantities of electrical energy are imparted into the steel scrap using carbon electrodes. The large amount of electrical energy causes the steel scrap to melt. Once again additives are added to the liquid steel scrap to form the desired steel grades [15], [18].

Secondary metallurgy

At the secondary metallurgy phase the steel undergoes further treatments. These treatments can be any of the following:

- Sulphur removal or sulphide modifications;
- Addition of micro-alloy powders to improve mechanical properties; and
- Lead injection to increase the machinability of the steel [18].

Once the secondary metallurgy treatments are complete, the steel is ready for casting.

Steel casting

Ingot casting and continuous casting are the two different casting methods. With ingot casting the steel is cast into an ingot mould and allowed to solidify. It is then heated and rolled into blooms or billets. The continuous casting process produces blooms, billets and slabs directly from the caster. Apart from the advantage of better efficiency, it also improves the steel quality and yield [15].

1.3.6 Steel rolling and finishing

Steel is worked through the rolling and finishing processes to achieve the final required steel properties. The rolling and finishing process consumes approximately 1.5-3 GJ of energy per tonne crude steel [9]. The main rolling processes can be divided into hot and cold rolling and finishing. Various rolling processes are used to achieve different steel properties [18].

Hot rolling and finishing

Rod, bar, plate and section profiles are all products produced through hot rolling [18], [20]. Blooms, billets and slabs are fed into a reheating furnace. The heated steel is passed through a series of mill stands to achieve the desired profiles. The steel goes through edge trimming and size cutting for the final finishing process to meet the required dimensions [18].

Cold rolling and finishing

Hot rolled steel strips go through cold rolling to improve the tensile strength, yield strength and surface finish. Annealing and temper rolling processes are performed after cold rolling to attain the desired degree of stiffness and surface finish [18].

1.4 Problem statement

The rapid expansion of the Chinese steel sector since 2000 has placed the global steel sector under significant pressure. The state of overcapacity in the global steel sector forces all steel producers to reduce their steel prices to stay competitive.

South African steel producers must find the means to reduce production costs to remain competitive within the local and global steel sectors. Urgent cost saving initiatives should be identified and implemented by local steel producers to be competitive.

1.5 Research motivation

Several studies investigated energy and cost saving opportunities for steel production facilities [16], [21], [22], [23]. Except for heat recovery, limited opportunities were identified for sinter plants.

Lu *et al.* [24] conducted a study where they investigated the potential for remaining cost saving opportunities on steel production facilities. The study showed that the cost saving margin for iron and steel making is very limited due to process constraints. Cost saving initiatives on the raw material preparation and especially the sintering process are much more evident.

In their study, they also noted that small improvements in the sintering process could lead to significant cost savings downstream in the steel production process. This creates the need to investigate more energy and cost saving initiatives on sinter plants.

1.6 Research objective

The main objective of this study is to investigate and evaluate cost savings initiatives on sinter plants. The following cost savings initiatives are covered in this study:

- Energy efficiency initiatives;
- Process optimisation; and
- Process scheduling.

A method for evaluating the cost saving initiatives are developed. Relevant cost saving initiatives are evaluated based on the following:

- Cost savings potential;
- Required capital expenditure;
- Ease of investigation;
- Feasibility and implementation requirements, and
- Sustainability and continuous attainment of operational targets.

The developed evaluation model is applied to a case study sinter plant. All relevant cost saving initiatives were evaluated for the specific plant. The most feasible initiative identified with the developed evaluation model is further investigated with the intention to be implemented.

1.7 Overview of dissertation

Chapter 1

Chapter 1 provides the background to and importance of the study. The South African steel industry and global steel markets are investigated. An overview of the steel production process is provided. The problem statement, research motivation and objective are explained which also act as the boundaries for the study.

Chapter 2

Chapter 2 is a brief background on the sintering process. Sintering cost saving initiatives are analysed from literature. Evaluation models used in literature are reviewed to gain insight during the evaluation model development. The investigation extends to operational and production factors that influence the feasibility of a cost saving initiative.

Chapter 3

Chapter 3 provides the methodology to develop the cost saving initiative evaluation model. The method to use the evaluation model to perform the sinter plant cost saving investigation is also discussed in this chapter.

Chapter 4

Chapter 4 provides the details for the evaluation model for a specific case study sinter plant. All the listed cost saving initiatives are evaluated for the specific case study. Results obtained from the evaluation model are explained. After evaluation, the most prominent initiative is further investigated for implementation.

Chapter 5

Chapter 5 concludes the study with reflecting on the ideas identified from the literature. Results are reviewed and recommendations are made for further studies.

2. Literature study

This section covers a literature study of existing cost saving initiatives. Evaluation models and initiative barriers are also reviewed.

2.1 Preamble

This chapter provides an in-depth literature study to have a better understanding of the sintering process. Different cost saving initiatives from literature are reviewed and analysed. The investigation is extended to determine the cost saving initiative barriers experienced during other studies. Lastly several initiative evaluation models from literature are reviewed and discussed after which the chapter is concluded.

2.2 Overview of the sintering process

Sinter is fine iron ore and other waste material melted together into clustered material of a suitable size to be charged into the *BF*. Other waste materials are a mixture of coke breeze, anthracite, limestone, dolomite, mill scale, sinter fines and flue dust [8], [10]. A simplified process flow diagram (PFD) of a typical sinter plant with the main components are provided in Figure 6 below.

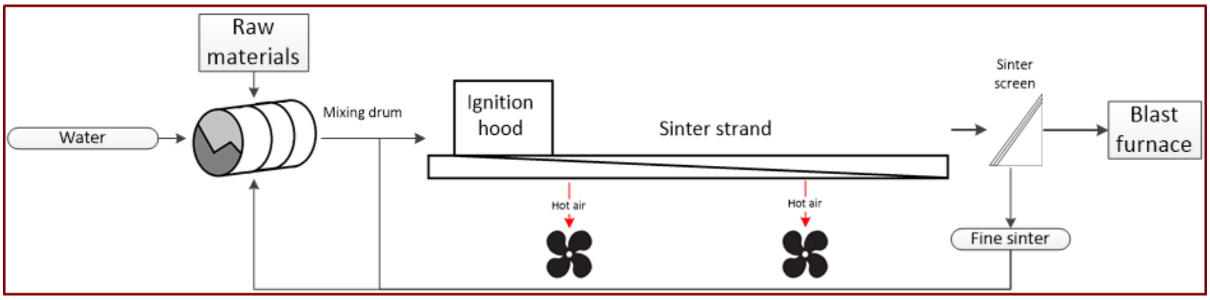

Figure 6: Simplified sinter plant process flow

All raw materials are weighed off and transported to the mixing drum. The mixing drum is used to mix all the raw materials to attain the required sinter composition. Water can be added to the mixture inside the mixing drum so that the finer raw materials can adhere to the coarser particles. The raw material mixture is then spread evenly across a continuous, moving grate known as a sinter strand [8].

The ignition hood located above the start of the sinter strand ignites the fine coke and anthracite particles in the mixture. *COG* or natural gas are typically used in the ignition hood to provide the required heat. Ignition of coke and anthracite occurs above 1300°C. After ignition the combustion is self-sufficient to cause surface melting and material clusters form throughout the sinter strand [8].

Large induced draft fans draw combustion air through the sinter strand. The sizes of the fans typically range between 2 MW and 5 MW [8]. The air draft through the sinter strand assists to complete the combustion throughout the entire sinter strand [10].

After the sintering is complete, the clusters of sinter are crushed and screened to meet specific size requirements [10]. Clusters that meet the size requirements are fed into the *BF* whilst undersized clusters, referred to as sinter fines, are returned to the mixing drum where the process is repeated [10].

2.3 Energy and cost saving initiatives on sinter plants

2.3.1 Preface

Several reports and publications on energy consumption and energy efficiency technologies are available. Implementing energy efficiency technologies impose opportunities to achieve significant cost benefits [25]. He and Wang [16] stated that although all of these energy technologies are available, the popularity of implementing them needs to be improved.

Yoon *et al.* [26] identified energy consumption to be the least important consideration by manufacturing companies when acquiring new equipment. This aspect can no longer be ignored in the South African steel manufacturing context as ever-increasing energy costs are making it almost impossible for local manufacturers to compete in the global market.

The suggestions of Lu *et al.* [24] (refer Section 1.5) has prompted further investigation into possible cost saving opportunities in the preparation of raw materials in sinter plants. The remainder of Section 2.3 explores these opportunities.

2.3.2 Heat recovery

A steel production plant in the Netherlands achieved a fuel saving of approximately 0.55 GJ per tonne sinter by implementing a heat recovery system. The heat recovery system also increased their electricity generation by approximately 56 kJ per tonne sinter. The payback period on this improvement was estimated to be 2.8 years with a capital investment of approximately R61.36 per tonne sinter [27].

It is common practice in Japan to use waste heat boilers for steam generation. The boilers use the recovered waste heat from the warm sinter waste gas to generate steam. Heat recovery of 0.25 GJ per tonne sinter was reported through the use of such waste heat boilers [27].

McBrien *et al.* [20] conducted a study to determine the amount of heat energy that is lost during the steel manufacturing process. Dry cooling the sinter to preheat the input air and recirculation of warm exhaust air were two heat recovery opportunities that were identified in the sintering process.

In the study, McBrien *et al.* did not take the ignition hood gas fuel into consideration. Although generally a small energy source within the entire sintering process, inclusion of the ignition hood gas fuel to the energy inputs may be beneficial. Increased energy inputs will increase the amount of heat available for recovery.

The Conch Cement Plant in China installed a waste heat power plant. On estimation, this provided an additional 9000 kW of electricity for use in their clinker production of 5000 tonnes per day [28].

Zhang *et al.* [29] investigated Chinese steel making practices to quantify energy savings and capital investments made on steel plants in China. This investigation which only focussed on major Chinese steel enterprises found that a typical energy saving of 0.35 GJ per tonne sinter was possible through waste heat recovery systems.

The potential for energy saving by smaller steel production facilities could be significantly higher as smaller facilities are typically less efficient than the major players. Capital investments made by the major Chinese steel producers for waste heat recovery systems are approximately R4.5 per tonne sinter [29].

Significant amounts of heat are present around the ignition hood, as a result of the combustion of coke and fuel materials in the sinter mixture. The literature review proved that several heat recovery initiatives are available to attempt heat recovery.

The methods as described above can be used or adapted to assist with heat recovery at the sinter plant. Heat recovery initiatives are possible with the following warm waste gases that are freely available at the sinter plant:

- Ignition hood exhaust gas;
- Sinter waste gas in wind boxes; and
- Sinter waste gas in exhaust stacks.

Heat recovered from these waste gases can be utilised to:

- Preheat the combustion air to the gas burners;
- Preheat the induced draft air to the sinter strand; and
- Generate high pressure steam for steam turbine power generation.

Important implementation considerations when investigating heat recovery systems are:

- Space limitations on site can cause difficulties with heat recovery system installations;
- Corrosive effect of particles contained in high temperature sinter flue gases on boiler walls;
- Heat recovery systems require large capital investments;

- The flow rate of the waste heat streams should be investigated to determine the feasibility of the project; and
- Integration of waste heat recovery systems with existing processes can be complex [30].

2.3.3 Oxygen and fuel enrichment

The Kobe Steel Group in Japan enriches combustion air with oxygen which is injected below the ignition hood. This oxygen enrichment narrows the heating zone, increases the flame front speed (*FFS*) and improves coke consumption. By injecting oxygen at a rate of 500 Sm^3/h, sinter production can be increased by 1 t/h [31].

Uneven heat patterns within the sinter bed during the sintering process, can lead to inefficient sinter making. Cheng *et al.* [32] investigated the possibility of controlling the heat patterns by enriching the sintering process with gaseous fuel.

They partially substituted the solid fuels with an ultra-lean methane concentration of 0.5% of total combustion air volume. With this gaseous fuel injection, a secondary self-sustained secondary combustion zone was achieved. The heat generated by the initial combustion zone provided the heat required for the gaseous fuel combustion.

The secondary combustion zone pre-heats the combustion air and maintains the melting temperature for a longer period thereby increasing both the sinter strength and quality. A 1.44% sinter strength improvement was obtained with a calorific heat input reduction of 4%.

The imbalance in heat distribution was further improved with gaseous fuel segregation. This entails the adjustment of gaseous fuel concentrations throughout the sintering process. The optimum fuel segregation proved to be a 1% concentration adjustment per millimetre in sinter bed height.

Wang *et al.*[33] conducted a study to analyse and model the influence of oxygen enrichment on hot blast stoves. For specific safety reasons, the oxygen enrichment was limited to 4%. Their results indicate that domes reach the required temperature faster when air is enriched with oxygen.

The blast air and BFG volume flow were kept constant. The oxygen enriched air reduced the heating time for the stoves with 4.5 minutes each. By reducing the heating time, less BFG is required which implies less energy is required.

Guo *et al.* [34] investigated the influence of oxygen enrichment on furnace temperatures. The oxygen levels in the combustion air were raised with 14%. The oxygen enriched air improved the heating system efficiency and maintained the furnace temperature with 15% less fuel consumption.

The literature review indicated that oxygen enrichment improves combustion and reduces energy loss. Various examples were mentioned where benefits were derived from the implementation of oxygen and fuel enrichment. These initiatives can be adapted for use on sinter plants in the following ways:

- Enriching the combustion air supplied to the ignition hood with oxygen;
- Injecting oxygen into the combustion air used in the coke combustion process; and
- The addition of gaseous fuel to the sintering combustion air for improved sintering.

Although significant savings can be achieved, the following factors may influence the feasibility of implementing oxygen and fuel enrichment:

- Combustion air fuel enrichment was performed under ideal laboratory conditions. Experience proved that it is difficult to achieve the equivalent on actual plants.
- Oxygen is an oxidiser that supports the process of combustion; and
- Oxygen levels should be carefully monitored to ensure a safe working environment [35].

2.3.4 Segregated charging of materials

Segregated material charging is the arrangement of similar sized sinter particles. Segregation slit wires (SSW) in Figure 7 are installed in an arc formation to arrange the sinter particles according to size. Maintaining a constant particle size increases sinter permeability and sintering efficiency [27].

Figure 7: Segregation slit wires[5]

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[5] Images adapted from Steel Plantech [Online]. Available: https://steelplantech.com/product/ssw/

The arc formation causes an exponential increase in gap size between two consecutive wires. Larger gap sizes further away from the drum chute spread coarser particles on the bottom sinter layers [27]. A visual representation of the SSW working principle is displayed in Figure 8.

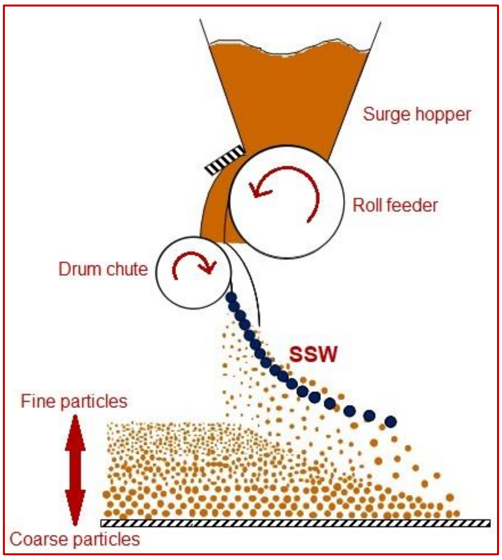

Figure 8: Particle distribution with SSW

SSW are installed on most steel production facilities in Japan. Equipment and installation costs are estimated to be approximately R13.2 million for a plant with a production capacity of 1 million t/a. This accounts for an approximated payback period of 2.4 years. Korea, China, Taiwan and India are next in line to make use of this segregated charging method on their sinter plants [36]. Four major improvements were identified when using the segregated slit wires compared to the conventional charging method:

- 5% improvement on productivity;
- Reduced coke breeze consumption by 2.8 kg per tonne sinter;
- Reduced amount of returned sinter fines; and
- Reduced lime consumption ratio [27].

The Rourkela steel production plant in India implemented a magnetic charging chute for improved segregated material charging by installing a ferrite type permanent magnet with a strength of 1200 gauss. The magnet reduces the velocity of the magnetic material particles dropping towards the sinter strand. Improved segregated charging is achieved as smaller magnetic particles are segregated onto the top layer of the sinter bed mixture. The following improvements were identified after implementing the magnet:

- Air filtration velocity improved by 20%;

- Plant productivity improved by 3%;
- Sinter yield increased by 1%;
- Returned sinter fines decreased by 3%; and
- Solid fuel reduction of 1 kg per tonne sinter [37].

Although the literature review indicated significant energy savings, the following considerations were highlighted regarding the segregated charging of materials:

- High capital cost;
- Expensive adjustments to existing charging equipment;
- Space limitations can restrict the implementation of new equipment;
- Regular maintenance to prevent material blockages between the segregated slit wires; and
- Quantification of expected savings is difficult and very site specific.

2.3.5 Production scheduling

Several studies indicate that the demand for electricity is on a strong increase across the world [38], [39], [40]. Forecasts predict that the increased demand will continue for at least the next decade. Bobmann and Staffell [41] found that electricity suppliers will find it extremely difficult to meet future demands.

Various incentives should be put into place to encourage the reduction of electricity consumption [41] and many initiatives have been implemented across the globe to reduce electricity consumption during high demand periods [42], [43].

Internationally, Zhao *et al.* [42] optimised the by-product gas system on steel plants. The gas systems were scheduled to achieve maximum electricity generation during peak tariff periods. Excess by-product gas is stored in gasholders and utilised for electricity generation during the peak tariff periods.

The process of reducing electricity consumption during peak tariff periods and increasing it during off-peak periods is called load shifting. The effect of load shifting on a power profile can be seen in Figure 9 as demonstrated by Vosloo [44]. The purpose of a load shift is to move the consumption from high tariff periods to lower tariff periods.

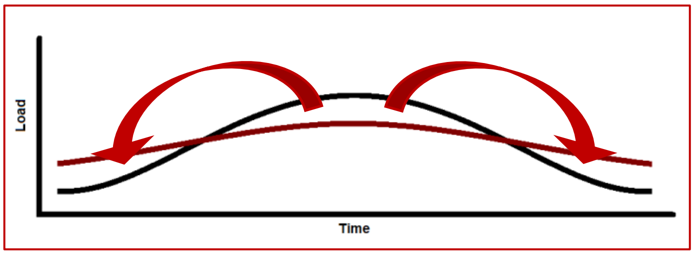

Figure 9: Load shift

The energy consumption result of a load shift for a complete cycling period typically remains energy neutral. This implies that the total energy consumed before the intervention is equal to that after the intervention for the same period of time [45].

Eskom, the national electricity supplier of South Africa, has implemented different TOU tariff periods based on electricity demand[6]. The present Eskom TOU periods are shown in Figure 10.

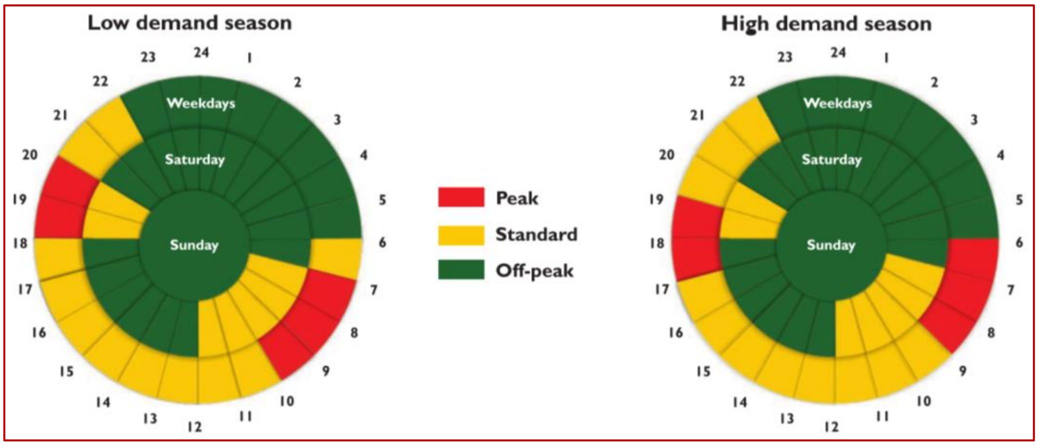

Figure 10: Eskom TOU tariff periods[7]

To promote electricity reduction initiatives, large electricity consumers can approach Eskom for funding selected electricity saving projects [46]. This implies that large capital projects associated with electricity savings that were previously beyond reach can now be funded.

Deysel *et al.* [47] implemented a project on a platinum mine in South Africa to reduce electricity costs. The control philosophy of five compressors was adjusted to minimise the electricity costs during peak tariff periods. The compressors were all rated between 4.3 MW and 4.8 MW. The project resulted in a reduction of 4.35 MW on electricity consumption. As the power ratings of sintering fans are similar

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[6] Eskom, Tariffs and Charges 2017/2018 booklet. [Date accessed: 2017-07-07]

[7] Eskom time-of-use tariff period wheels obtained from Eskom, Tariffs and Charges 2017/2018 booklet. [Date accessed: 2017-07-07]

to those of the compressors used in the Deysel *et al.* example, the same proposed control philosophy can be adopted for sintering fans.

It should therefore be possible to schedule sinter production such that excess sinter can be stock piled during off-peak tariff periods and consumed during peak tariff periods. With this approach electricity and gas consumption for sinter production can be reduced during peak periods. The excess gas available in the gas system during peak periods could be utilised for supplementing electricity requirements during such periods.

Variable speed drives (VSDs) or soft starters can be used to reduce the electrical load and strain on the large fan motors [48].

The scheduling of sinter production according to TOU periods can achieve large electricity cost savings. The feasibility of scheduling sinter production is influenced by the following:

- Stock piles should be large enough to store sufficient sinter for meeting the demand during the peak periods;
- Production capacity should be higher than the demand rate;
- Capital for funding electricity saving initiatives can be funded via Eskom;
- Savings are, to a very large extent, site specific; and
- The installation of VSDs should be considered.

2.3.6 Automated sinter control

Fan *et al*. [49] developed an automated control system for improving labour productivity, sinter quality and achieve energy savings. A control system was developed for analysing and predicting the plant performance resulting from process parameter changes. The system analyses chemical composition, sinter permeability and sinter temperatures. Despite stating that the control system was also developed to achieve energy savings, no saving information was provided.

Zambaldi *et al.* [50] proposed a low cost, automated control system for controlling temperatures during steel heat treatments. An open source Arduino platform was utilised for developing the control system. A simple system consisting of a thermocouple, Arduino, solid state relay (SSR), proportional–integral–derivative (PID) algorithm and a liquid crystal display (LCD) was used for automating the temperature control.

A reduction of 6% in energy consumption was observed after implementation. The Arduino control system proposed by Zambaldi costs approximately R1600[8], 42% less than other controllers that are commercially available. The low cost and simplicity of the Arduino provides a feasible option for investigating the automation of sinter plant controls.

The Arduino control system can be adapted for automated control on the sinter plant. Thermocouples can be installed in the ignition hood and in wind boxes below the sinter strand. The following may influence the feasibility of sinter control automation:

- Arduino control systems are reasonably affordable but thermocouples and other auxiliary equipment are expensive; and
- Due to the significant return on investment for system automation most plants already utilise automated control systems.

2.3.7 Optimising sinter bed properties

Higher production can be achieved by increasing the sinter bed depth and simultaneously reducing the strand speed. For this operation, it is essential to have a high permeability. Improved granulation will increase the permeability of the sinter [31].

Reports by Burns Harbour works, within the Bethlehem Steel Group, showed an increase in productivity of almost 30% by raising the bed depth from 406 mm to 635 mm and reducing the strand speed from 2.4 m/min to 2 m/min. Khouzestan Steel Company (KSC) also reported a 6% increase in productivity by increasing the sinter bed depth at the Mizushima works in Japan from 530 mm to 700 mm [31].

In the study by He and Wang [16] it is mentioned that a fuel saving of 23.64 MJ per tonne sinter was achieved with a 10 mm increase in sinter bed depth. The capital cost required for the improvement was more than R5 million with a payback period of 1.6 years.

The feasibility of optimising sinter bed properties is influenced by the following:

- Equipment limitations can restrict the adjustment of the sinter bed depth;
- High level of metallurgical sinter knowledge is required for a good investigation;
- Although the payback period may be less than two years, the present financial situation at most steel production facilities may limit any capital projects; and

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[8] Based on prices in September 2015 and a currency of R13.50 per US$

- Although productivity can increase with an increase in bed depth, a reduction in sinter quality may be experienced.

2.3.8 Reductions in air leakage

Exhaust stacks at the fan outlets consists of residues of combustion gas (used for coke and anthracite combustion), suction air (utilised for cooling the sintering strand) and mechanical air leakage (air drawn in through gaps in the mechanical equipment). As a result, the volume of exhaust gas at the fan outlets can be calculated as follows:

Equation 1: Composition of the exhaust gas on the exhaust outlet

$$EG_T = CG + SG + AL$$

where EG_T represents total exhaust gas volume;
CG represents combustion gas volume;
SG represents suction gas volume; and
AL represents air leakage volume.

From Equation 1 it should be evident that the volume of gas that passes through the fans can be reduced by reducing the amount of mechanical air leakage inside the system. A reduction in the volume of gas passing though the fans will reduce the amount of electricity required by the fans for extracting the volume of gas [51].

Takashima *et al.* [51] reported on air leakage countermeasures that were implemented at the fourth sinter plant in Chiba in the Kawasaki Steel technical report. Improvements to reduce the air leakage on the plant resulted in:

- A reduction in electricity consumption at the fans;
- A reduction in furnace fuel; and
- Increase in productivity without increasing the blower capacity.

The countermeasures implemented at this plant to reduce air leakage were:

- Diagnostic techniques to identify abrasion spots in machinery;
- Analysis of oxygen levels in exhaust gas;
- New air seals between sinter pallets and slide beds;
- Corrosion resistance lining inside ducting;
- Switch to high FeO sinter production to increase temperature at discharge end;
- Installation of drum feeder for better raw mix feeding;
- Side press rollers for improved raw sinter compression; and
- Uniform ignition at line burners;

After implementing these countermeasures, the following measured improvements were achieved:

- Air leakage reduction of 14% in the total exhaust gas volume;
- Heating furnace fuel reduction of 25.1 MJ per tonne sinter; and
- Electricity reduction of 7.2 MJ per tonne sinter.

Lidbetter [52] and the Environmental Protection Agency [27] quoted results obtained by Worrell [53] which indicated that repairs to fan ducting and reduced air leakage can reduce the power consumption of fans. A saving of approximately 0.014 GJ per tonne sinter was achieved through air leakage reduction. The cost of repairing air leaks on fan ducting is estimated at approximately R1.82 per tonne sinter and has a payback period of approximately 1.3 years.

Nakamura *et al.* [54] investigated the development of new measuring systems which included the measurement of air leakage. Their air leakage measurement system utilises a laser-run oxygen densimeter which is installed in the fan ducting below the sinter bed. The amount of false air sucked in through air leaks is determined by analysing the amount of oxygen present in the fan ducting.

The literature on air leakage reduction indicated that there are several means for monitoring and minimising air leakage on sinter plants. Although significant savings can be achieved by reducing air leakage, the following could influence project feasibility:

- The implementation costs and savings are site specific [27]; and
- Installation of oxygen analysers have a short payback period and are therefore already implemented at most sinter plants.

2.3.9 Sinter quality optimisation

Sinter quality optimisation has proved to be one of the most favourable opportunities for improved efficiency in the manufacturing of iron [24]. Sinter quality is rated according to the following indices:

- Strength;
- Reduction degradation index (RDI);
- Reducibility index (RI);
- Fines content;
- Sinter size;
- Chemical composition; and
- Productivity [31].

Sinter strength

Cheng *et al.* [55] proved that melt quantity index (*MQI*) is a good indicator to measure sinter strength by altering process parameters. *MQI* is the initiating temperature at the start of the melting process above 1100°C.

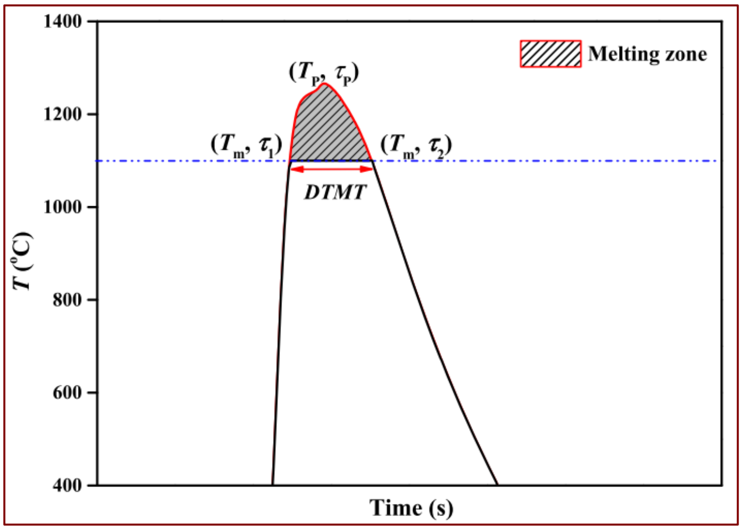

Figure 11: Definition of melt quantity index [55].

According to Figure 11, the MQI can be calculated by means of the following integral:

Equation 2: Melt quantity index integral

$$MQI = \int_{\tau_1}^{\tau_2} (T - 1100) \cdot d\tau$$

Cheng *et al.* [55] further examined the effects of carbon content, sintering pressure and fuel reactivity on the MQI. The effects of the fixed carbon content were examined by increasing the fixed carbon content from 3.26% to 3.70%. It was found that the increase works efficiently up to a point where the reaction became oxygen-limited. Further increases were achieved by increasing the oxygen supply.

The study by Cheng *et al.* confirmed that if the carbon content is too low the MQI is reduced which results in a low-quality sinter. If the carbon content is too high the excessively high MQI leads to low porosity sinter which causes higher energy consumption at the *BF*. It is therefore important to find a good balance in carbon content to achieve good quality sinter with good porosity.

The sintering pressure was changed from 10 kPa to 14 kPa. The results indicated that sinter strength cannot be ensured when sintering pressure is too high. When the sintering pressure is too low the sinter productivity also decreases due to a decrease in sintering speed. Sintering pressure should therefore be optimised to find the required balance between sinter strength and productivity.

A third study by Wang was to investigate the fuel reactivity on the sinter strength. The fuel reactivity on the sinter strength was investigated by keeping the carbon content and the sintering pressure constant. Different ratios of more reactive charcoal and less reactive coke breeze were utilised. Results indicated that the sintering time decreased as the fuel reactivity increased. The excessively high fuel reactivity led to an increase in *FFS* and uneven fuel combustion through the sinter bed. By increasing the FFS the sintering speed is increased and the MQI is reduced. It is therefore important to find an optimal ratio for balancing the sintering speed and MQI.

Following the study on fuel reactivity Cheng *et al.* also stated that performance parameters such as combustion and utilisation efficiencies have a large influence on sinter strength. The combustion efficiency was investigated by analysing the off-gases resulting from the fuel combustion process. Results indicated the amount of oxygen near the igniting particles will influence the MQI. With a higher combustion efficiency, the MQI can be increased as more heat can be generated and applied to the melting process.

Utilisation efficiency is defined by the following formula:

Equation 3: Utilisation efficiency

$$\eta = 1 - \frac{|HTFS - FFS|}{HTFS}$$

Cheng *et al.* stated that the MQI is highly dependent on η. η Assists with the melt phase formation which leads to a higher MQI. Heat transfer front speed (HTFS) is dependent on the packed structure of the sintering bed, the air flow rate and the raw material properties. Wang stated that η should ideally be maintained at approximately 1.

The tumbler index (TI) provides a further alternative for measuring sinter strength. This index indicates the size reduction that might take place during the sinter handling processes from the sinter plant to the *BF*. The index is largely related to the properties of the sinter matrices that form during the sintering process [31].

Reduction degradation index

The transformation during the reduction of hematite to magnetite is known as degradation. Degradation generally leads to volume increases which in turn causes structural stresses in the sinter [31].

The sinter *RDI* is used to predict the sinter degradation in the *BF*. A low RDI will also ensure stable and smooth *BF* operations [56]. In a study conducted by Mochón *et al.* [31] it is stated that the ambient temperature and the titanium content in the sinter have a large impact on the sinter RDI.

An increase in the levels of magnetite in the sinter mixture will decrease the sinter RDI. Coke consumption in the *BF* can also be reduced with higher magnetite levels. The bed temperature increases as the magnetite oxidises to hematite in an exothermic oxidation reaction [31].

High alumina (Al_2O_3) and titania (TiO_2) levels in the sinter mixture will increase the RDI during the reduction of hematite to magnetite. The increased volume increases stresses in the sinter and the permeability of the burden is reduced. Results indicate that an improvement of 6% in sinter RDI reduces the *BF* coke rate by 14 kg per tonne of hot metal and an increase of 3% in *BF* productivity [31].

Reducibility index

Sinter reducibility is the ability to transfer oxygen during reduction in the *BF*. Sinter structure and porosity are closely related to the reducibility of the sinter. Heterogeneous structures are more reducible than homogeneous structures. Hematite (Fe_3O_2) and magnetite (Fe_3O_4) are quickly reduced to wustite (FeO). Sinter with large surface areas and high porosity is more reducible [31].

Fines content and sinter size

Sinter cakes are screened according to size, generally ranging from 5 mm to 40 mm, and are directly fed into the *BF* hoppers. Sinter cakes exceeding 40 mm are crushed into smaller sizes before being rescreened whilst sinter fines (sizes smaller than 5 mm and also known as returned fines) are recycled back to the sinter hoppers. The returned fines are used in the sintering process to cover the sinter strand with a pre-sintered layer [31].

A balance should be maintained between sinter generation and the recycling of returned fines. Mochón *et al.* [31] stated that a good ratio between sinter generation and recycling of returned fines is

$$0.95 \leq R_B \leq 1.05$$

where R_B is the balance ratio calculated as

Equation 4: Sinter balance ratio

$$R_B = \frac{Sinter\ generated}{Fines\ returned}$$

The R_B can be altered by changing sinter sizes and productivity can be increased by reducing the number of returned fines. The amount of returned fines can be reduced by reducing the screened fines size [31].

Chemical composition

The chemical and structural composition of the sinter is very important as it supports the stability of *BF* operations. Good quality sinter normally have a high iron content, a low gangue content and a basicity ranging from 1.6 to 2.1 [31].

The sinter *RI* and sinter quality usually improve with hematite levels higher than magnetite levels. A 2% increase in wustite (FeO) improves the *RDI*, but with FeO-levels too high the RI is reduced. The amount of FeO should therefore be optimised to increase the RDI without altering the sinter quality [31].

Sinter RDI also increases as the amount of alumina (Al_2O_3) in the sinter is increased. A higher alumina content reduces sinter strength as the alumina increases the viscosity of the primary melt of the sinter. The primary melt of the sinter is formed by the temperature increase as the fuel in the sinter mixture ignites. High levels of alumina cause irregular pores in the sinter thereby weakening the sinter structure [31].

Magnesia (MgO) assists with the optimal formation of *BF* slag. MgO can be added to the *BF* burden by charging dolomite, dunite or sinter into the furnace. The MgO reduces the CaO-levels in the sinter thereby reducing sinter strength, reducibility and productivity. It is therefore recommended that MgO is added directly into the furnace and not into the sinter mix [31].

The temperature point where primary melt formation occur can be reduced by adding lime (CaO) and silica (SiO_2) into the raw sinter mixture. The primary melt point is the minimum temperature at which strong sinter can be produced. The CaO and SiO_2 form low melting temperature compounds with the iron oxides. The formed compounds are highly dependent on the chemical composition of the sinter layers and surrounding particles [31].

Productivity

As for any production plant, productivity on a sinter plant is an important benchmarking characteristic used to measure plant performance. Large amounts of effort are invested to achieve high productivity. Good bed permeability, granulation and plant output are the three main variables which influence the productivity on a sinter plant. Uniformity, sinter bonding strength, sinter crushing and sinter fines influence plant output [31].

Productivity can be improved by replacing the addition of dolomite with olivine or serpentine. Dolomite, olivine and serpentine are added to the raw sinter mix to improve the MgO content. Olivine and serpentine are known to have less effect on sinter strength than dolomite [31].

Optimisation of sinter quality can present large cost saving opportunities provided that the following feasibility factors are considered:

- High level of metallurgical sinter knowledge is required for a good investigation;
- Sinter quality requirements are very specific for each *BF*; and
- Availability of raw materials can restrict sinter composition adjustments.

2.3.10 Summary

provides a summary of all the cost saving opportunities as mentioned in the above literature. This table will be utilised as a reference point for cost saving initiatives that are investigated in the remainder of this study.

Table 1: Summary of potential cost saving initiatives at sinter plants

Energy efficiency and cost saving initiatives identified on sinter plants	Fuel saving/improvement	Electricity savings	Capital cost	Payback period	Reference
Sinter plant heat recovery	0.55 GJ/t		R61.39/t	2.8	[27], [28], [29], [53]
Oxygen and fuel enrichment	15% reduction in fuel consumption				[31], [32], [33], [34]
Segregated charging of materials	79 MJ/t		R13.2 Million	2.4	[36], [37]
Sinter production scheduling		LS and PC projects of up to 4 MW	No capital required	n/a	[42], [47]
Automated sinter control	6% reduction in energy consumption		R1600		[49], [50]
Optimising sinter bed properties	23.64 MJ/tonne, up to 30% in productivity		R5.1 Million	1.6	[16], [31]
Reduction of air leakage		0.014 GJ/t	R1.82/t	1.3	[27], [51], [54]
Sinter quality optimisation	14 kg coke reduction/ tonne liquid iron at the BF and a 3% increase in BF productivity.				[31], [55], [56]

LS – Load shift, PC – Peak clip

2.4 Existing methods for analysing cost saving opportunities

2.4.1 Preamble

The detailed investigation to determine the final feasibility of a project can be a complex process. A review of existing methods for analysing cost saving opportunities will provide valuable insights into the development of a cost saving evaluation model.

2.4.2 Framework to reduce electricity costs in the South African steel industry

Breytenbach [57] developed a framework to identify feasible electricity cost saving projects. The framework provides a prioritisation function that assists with the identification of feasible cost savings opportunities. The prioritisation function consists of two parts which are multiplied to provide a final project feasibility rating.

The first part of the prioritisation function consists of a sum of fixed variables. The corresponding value for each of the fixed variables depends on the type of cost savings initiative and the available funding method. The variables can be determined without any detailed project investigations and only the expected project type and expected funding model are required.

The total power usage and electricity intensity rankings for each project must be determined for the second part of the prioritisation function. These rankings are project and site specific and therefore require more detailed investigation before ranking values can be allocated.

The framework provided the following insights:

- Project rating method was used to identify feasible cost savings projects;
- Specific fixed variables are allocated to different electricity saving initiatives;
- The influence of energy intensity on the feasibility of a project; and
- Different funding models are available to increase the priority of implementing a large capital projects.

Breytenbach verified and validated his framework on two case studies. Although this study solely focussed on electricity cost saving projects, insights gained from this study can be used in the development of a cost saving initiative evaluation model.

2.4.3 Rating strategy for energy saving initiatives on mines

Schutte [58] developed a method to identify and rate the most appealing energy savings projects on deep level mines. The method utilises a risk matrix and project appeal indicator to rate each energy saving project. The risk factor is rated according to likelihood and severity.

The risk factor for project implementation is obtained by multiplying the likelihood and severity ratings of each project. Specific values are allocated to fixed variables to be used as weights. These weights are multiplied with the risk factors to obtain an overall project risk rating.

Each project consists of different aspects that effect the desirability to implement the specific project. A score is allocated to each aspect based on its sufficiency and desirability. The score is obtained by multiplying each aspect's sufficiency and desirability ratings. Finally, the project appeal indicator is determined by the sum of all aspect scores of the project.

Schutte also verified and validated his method. Although Schutte only applied his method to deep level mines, many insights from his work can be used in the development of a cost saving initiative evaluation model. The following insights were obtained from his method:

- Project rating method was utilised for identifying feasible cost savings projects;
- Weights are used to emphasise the influence of important aspects;
- Desirability ratings were linked to project implementation aspects which can act as a guideline for determining the importance of each project implementation aspect;
- The influence of utilisation and availability on the feasibility of a project;
- The influence of prior investigations;
- Ideas to improve the efficiencies of large industrial fan systems; and
- Schutte verified and validated his method;

2.4.4 Compressed air energy savings on an iron production plant

Zeelie [59] developed a generic method for implementing an energy saving strategy on the compressed air of an iron production plant. His method was used to identify a project to effectively reduce the supply pressure on a compressed air system by approximately 20 kPa. This energy efficiency project saved approximately 1.2 MW.

Using data and information from a high-level plant investigation he determined operational limits and critical constraints. Different cost saving strategies were tested for the compressed air system to determine if the system complied with the applicable limits and constraints. He also validated and verified his results.

Zeelie used a non-commercial simulation package to simulate the effect of the energy efficiency project on the compressed air system. Linear regression models were used to quantify the energy saving on the compressed air network.

Insights from the methodology developed by Zeelie are:

- The importance of the availability of sufficient data and information to allow the specification of operational limits and critical constraints;
- The steps in the methodology can assist with the development of a cost saving evaluation model;
- A non-commercial simulation package can be used for simulation; and
- Linear regression models proved to be an effective means for quantifying savings through energy efficiency projects.

2.4.5 Analysing electricity cost saving opportunities on South African gold processing plants

Hamer [60] investigated the cost saving potential of implementing electrical load management interventions. A method was developed for identifying feasible load management projects on gold processing plants and was used to identify two different load management projects on separate gold processing plants.

The initial step of his methodology was to obtain data and measurements to construct a data inventory. This was followed by a characterisation of the plant according to energy consumption, operational limits and constraints. Different cost saving initiatives are investigated with the final steps being baseline development and simulations.

Hamer implemented two projects where he optimised the production schedules similar to the proposed cost saving opportunity as described in Section 2.3.5 above. Profile baselines were utilised to quantify the possible cost savings and a custom simulation was developed in Excel to schedule the production for maximum cost savings.

Insights from the Hamer methodology are:

- The importance of reliable data and information;
- The approach can be utilised for the development of a cost saving evaluation model;
- Project evaluation criteria (Payback period, implementation effort, operational effort and product quality) to be considered;
- A profile baseline is an effective means for quantifying savings in load management; and

- A custom Excel simulation can be used for investigating feasibility.

2.4.6 Structured industrial energy efficiency program

Kikonyogo and Bosman [23] developed and applied a structured industrial energy efficiency program on a steel plant case study. The program consists of three stages and the objectives for each stage are as follow:

1. **Opportunity identification** - Compile a list of all possible energy saving projects and highlight the most feasible and attractive projects for further investigation. The most attractive projects are highlighted for further investigation.
2. **Master plan** – Further investigations of the highlighted projects and familiarisation with plant processes and constraints.
3. **Implementation** –Implementation starts with simple quick wins and progress towards complex projects.

Although Bosman and Kikonyogo applied their structured industrial energy efficiency program to a steel production facility, raw material preparation plants were neglected the during their investigation. Insights obtained from their program which can be used in the development of a cost saving initiative evaluation model include:

- The three-stage approach;
- Rating of opportunities according to payback period and business impact; and
- Specifications provided for energy saving project implementations.

2.5 Challenges experienced by cost saving initiatives

2.5.1 Major role of capital requirements

Cost saving investments face restrictions that may prevent a company from implementing a cost saving initiative. A study by Mac Nulty [61] indicated that the availability of capital is the largest barrier to the implementation of cost saving initiatives. The ratings of the identified barriers are shown in Figure 12 below.

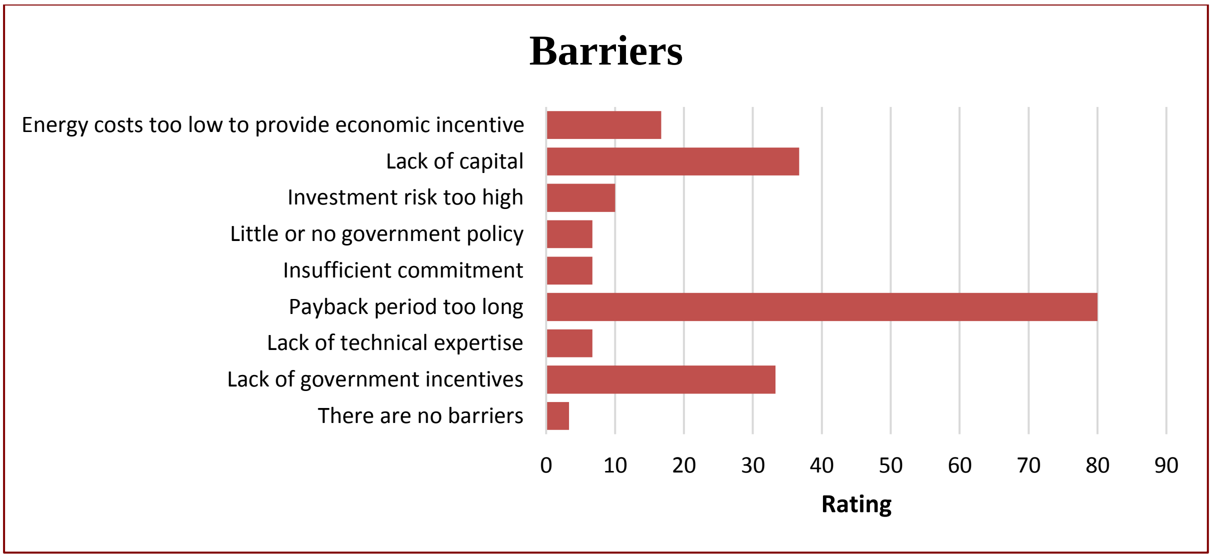

Figure 12: Cost saving investment barriers

The critical financial situation of local steel producers was highlighted in Chapter 1. This situation led to limited capital availability for new projects and development. The study by Mac Nulty confirmed that capital investments and payback periods are the dominating barriers to cost saving investments.

As a result, these two barriers will be factored into the development of a cost saving initiative evaluation model.

2.5.2 Business factors

Lidbetter [52] indicated that the success of any business can be rated as follows:

- Environmental factors;
- Market conditions; and
- Energy costs.

Lidbetter quoted results by Worrell where he determined the level of importance of each of the above business factors and the results from the study are summarised in Table 2. In this table, business factors are ranked according to importance with 5 being very important and 0 being unimportant. It must be noted that *Identifying and implementing cost saving measures* is not considered as a high priority.

Table 2: Business rated factors [52]

Business factor	**Ranking**
Meeting regulatory requirements	5
Meeting production schedule	4.5
Maintaining product quality and consistency	4.3
Keeping up with new or shifting market demands	3.3
Having reliable, high quality electricity supply	3.3
Maintaining market niche	2.5
Keeping up technologically with competitors	2.3
Maintaining a happy and productive staff	2.3
Identifying and implementing cost savings measures	1.3

The rankings provided in this table should be kept in mind when developing a prioritisation model.

Worrell further investigated the reasons why the business factor, *Identifying and implementing cost savings measures*, has such a low priority ranking. The investigation identified the following barriers as the main reasons for the low priority ranking:

- Limited capital – Major improvements in energy efficiency are in most cases capital intensive. Large capital investments in a struggling steel industry is the key limiting factor.
- Production concerns – Steel plants are production driven. Maintaining production levels and meeting product quality is a very high priority for any production plant. Altering the production reliability will face serious opposition from plant personnel.
- Limited staff time – Implementing new energy efficiency projects will require additional time and effort from plant personnel. Energy efficiency projects will not receive priority over plant production.
- Information – Information on new equipment and energy efficiency projects is easily accessible, but additional time must be invested to make informed decisions.
- Reliability concerns – Installation of new equipment or altering production schedules may influence equipment reliability and maintenance. Reliability that may influence production will not be tolerated.
- Sustainability – If the savings of the energy efficiency projects are not considered to be sufficient, the project will be an inconvenience and less effort will be invested to sustain the project.

These barriers play a vital role in the successful implementation of any project. The barriers identified by Worrell can be grouped as follow (note that certain barriers may fall into more than one group due to common aspects):

- Capital requirements (Limited capital);
- Product quality (Production and reliability concerns);
- Investigation effort (Information);
- Implementation effort (Limited staff time);
- Operational effort (Limited staff time, reliability concerns); and
- Sustainability.

2.5.3 Project funding

The implementation of new equipment and systems for energy and cost saving measures generally involve large capital investment. In support of various other studies referenced throughout this document, a study by the OECD Steel Committee indicated that the largest barrier to any cost saving initiative is capital [61].

Santana and Bajay [62] investigated thirteen countries to investigate their approaches towards improved energy efficiency. Research funding, the setting of minimum performance standards and tax incentives are some of the initiatives that were identified.

Eskom, the national electricity provider of South Africa, has announced and implemented various funding models to encourage electricity savings projects. These projects are known as demand side management (DSM) projects and the funding of such DSM projects are less expensive than the building of additional power stations to meet the ever increasing demand [46].

DSM projects are divided into different categories and funding rates are also related to the savings margin of the specific project [46]. The project descriptions and associated funding options are provided in Table 3:

Table 3: DSM project categories

Project type	**Project description**	**Project funding**
Energy efficiency	Energy saving throughout the day	R 2.625 million/MW
Peak clipping	Energy saving during peak electricity demand periods	R 1.75 million/MW
Load shifting	Shifts energy consumption away from peak electricity demand periods	R 1.75 million/MW

Detailed investigations with specific compliant documentation are prerequisites for submitting a motivation for funding [63]. Despite the long payback period of energy efficiency initiatives, the availability of additional funding for such projects would increase their feasibility.

Additional funding enables large capital projects that were previously overlooked, to be reinvestigated. The capital barriers are therefore removed as less capital is required from the plant perspective.

2.5.4 Summary of initiative barriers

The literature review indicated that the implementation of new cost saving projects will face several barriers which may vary for each plant. These barriers can be grouped into the following ten categories which will be incorporated into the development of an evaluation model for cost saving initiatives:

Table 4: Summary of initiative barriers

Barrier	**References**
Capital requirements	[57], [58], [60], [61], [52], [62], [63]
Payback period	[61], [63]
Previous implementation	[57], [58]
Energy cost ratio	[57], [61]
Product quality	[52], [60]
Limited information for investigation	[52], [60]
Installation and implementation effort	[52], [60]
Operational effort	[52], [60]
Sustainability	[52], [60]

2.6 Conclusion

Various sinter plant cost saving initiatives were identified and investigated. Ideas from various sectors and plants have been adopted for possible implementation on sinter plants. Cost saving opportunity evaluation models have been assessed. Prioritisation functions and evaluation matrices proved to be effective means for rating and prioritising the most feasible projects.

The reviewed prioritisation models require detailed initial investigations and focus on different sectors and plants. Valuable insights were obtained from previous prioritisation models. The ten most common barriers which influence the feasibility of projects were identified. These barriers and methods will be utilised for developing a cost saving initiative evaluation model to accurately identify feasible cost saving initiatives on sinter plants.

3. Cost saving initiative evaluation model

This chapter explains the development and utilisation of the cost saving initiative evaluation model.

3.1 Preamble

This chapter defines a new model for evaluating cost saving initiatives on sinter plants and consists of two different functions. The results of the two functions are multiplied for each initiative to obtain an overall rating. The steps for conducting the detailed investigations and simulations which follow the evaluation process are also explained.

The literature review indicated that similar trends were followed by almost all cost saving initiative evaluation models. This should provide sufficient evidence to prove that a generic methodology can be developed for the evaluation of cost saving initiatives. In summary, the methodology consists of the following steps which are also represented in Figure 13 and is described in more detail in the remainder of this chapter:

- High-level plant investigation (development of a reasonable understanding of the processes and substantiating data and information);
- Initial cost saving initiative evaluation (rated list of possible alternatives based on initial feasibility evaluation); and
- Detailed investigation process (including baseline development and project simulation).

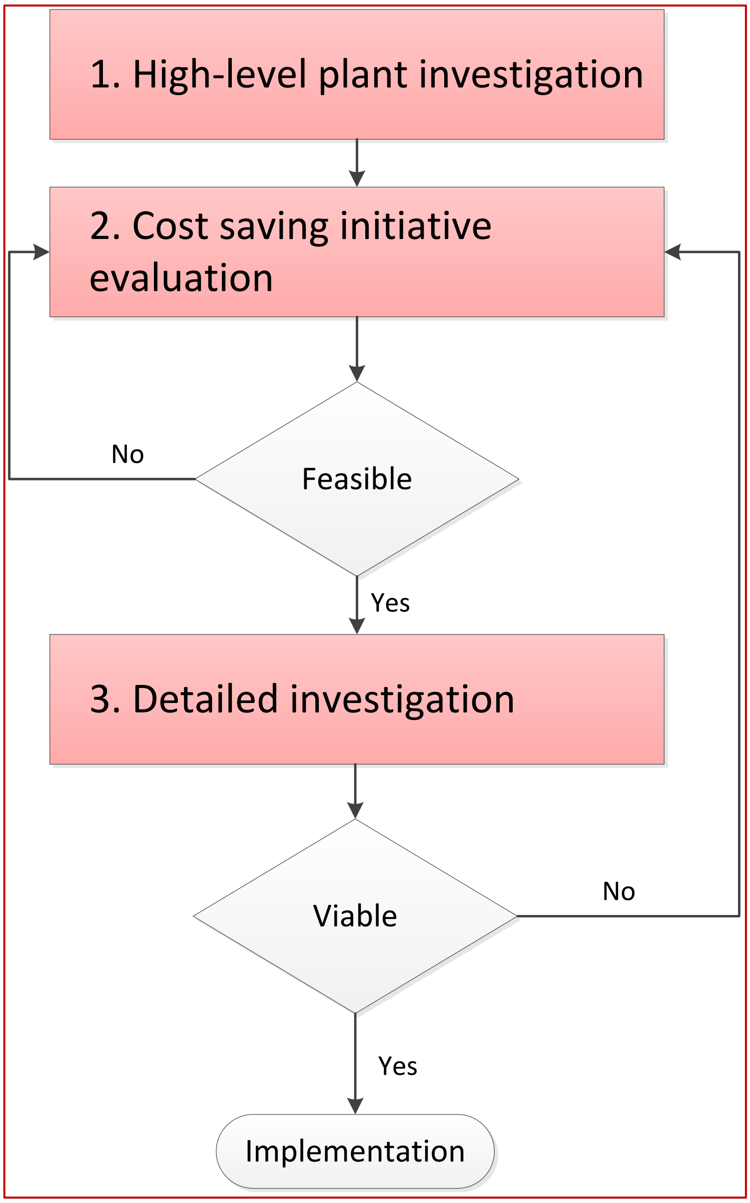

Figure 13: Overview of methodology

3.2 High-level plant investigation

The literature review indicated the importance of a high-level overview and understanding of the process and its various components. As a result, the initial step in the investigation is a high-level investigation of the plant to develop a basic understanding of the basic processes. This involves an informative plant walk through and a general overview of sinter plant operations. Knowledge of the plant is continuously increased as additional insight is gathered during the investigation into potential cost saving initiatives.

The various energy and operational specifications and measurements are provided in Figure 14. These specifications and measurements act as guidelines to assist with the plant investigation. Depending on the initiatives, certain specifications and measurements would be more relevant than others.

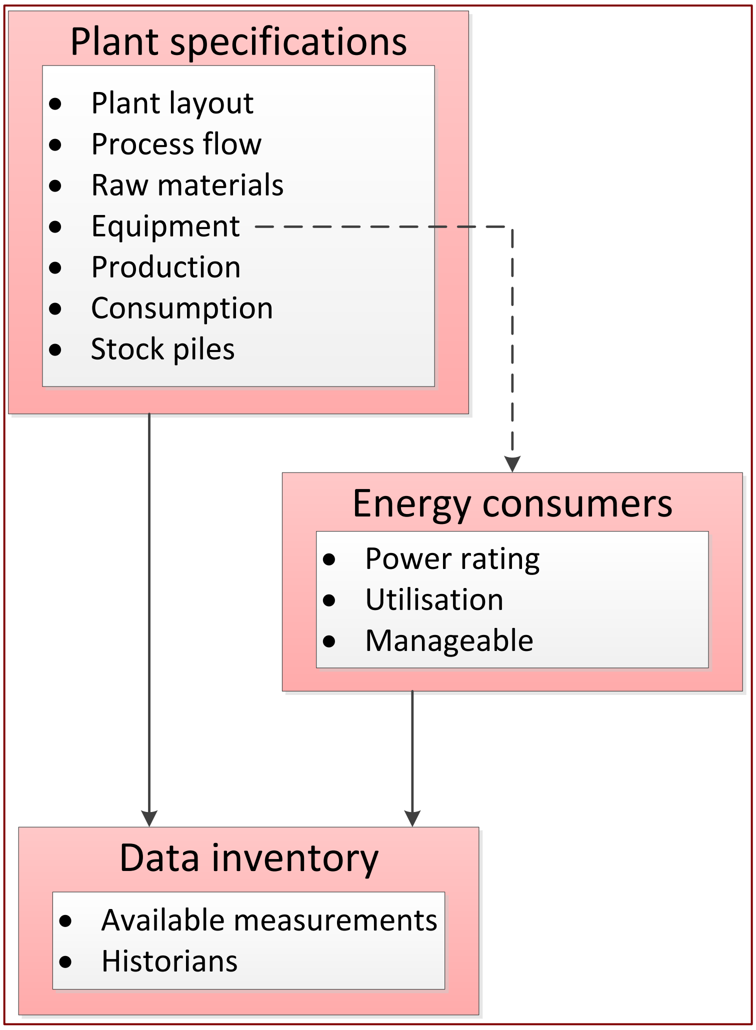

Figure 14: Plant investigation process

Plant layout and process flow

Plant drawings are beneficial for indicating plant equipment details and location. PFDs provide a high-level overview of the various processes. These drawings and diagrams should provide a reasonable understanding of the raw material and sinter mass flows through the sintering process. An example of a typical sinter plant layout is provided in Figure 15. Plant layouts and PFDs should be continuously updated with the latest information and are valuable information sources during plant investigation.

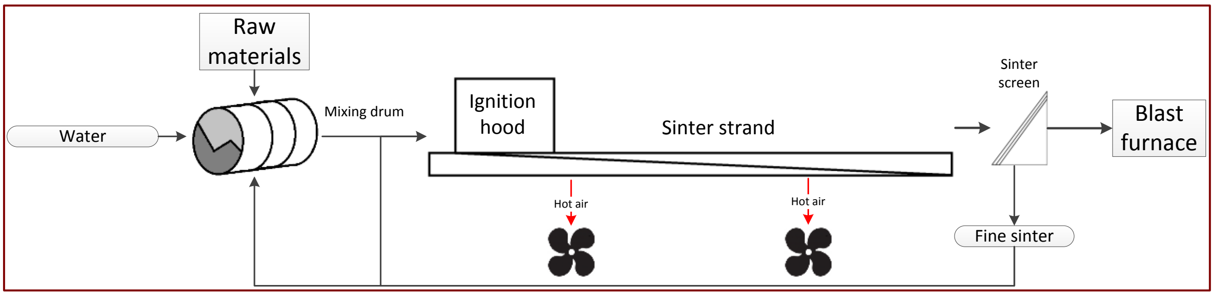

Figure 15: Simplified typical sinter plant layout diagram

A further valuable resource for assisting with the identification of cost saving initiatives is experienced plant personnel. Their extensive knowledge of the plant and daily, repetitive efforts to achieve production targets enables them to identify deficiencies and opportunities for improvement which would otherwise not have been recognised.

Raw materials

Raw materials play an important role in the efficiency of the sinter production process. High-quality raw materials with the correct chemical composition will improve the quality of the produced sinter. The mixture of raw materials can be varied to achieve different sinter attributes.

Based on the composition of the iron ores supplied to the *BF*, each *BF* might require sinter with different attributes. It might therefore be meaningful to investigate the optimal sinter mixture required by the specific *BF*.

Equipment

All the major equipment utilised by the sintering process should be identified and the energy consumption or power ratings required by each component must be determined. The investigation of equipment with low energy consumption or low utilisation may not be an efficient utilisation of investigation time.

The manageability of a specific piece of equipment entails the effort to adjust the operation of the equipment and its resulting impact on operations. The manageability of certain components might be critical to the overall operations on the plant and a thorough investigation should be conducted before any alterations are made to the existing operational procedures.

Production, consumption and stock piles

A sinter plant is designed to have a specific production capacity for meeting the sinter consumption requirements of the *BF*. Sinter production and consumption trends are compared to determine the margin between the sinter supply and demand. Stock piles are used as buffers to ensure that the supply can meet the demand.

Data inventory

A data audit should be conducted as the final step of the plant investigation process. Control system interfaces such as supervisory control and data acquisition (SCADA) systems should be examined to determine the available measurement data and trends. Meter locations and measuring points should be determined. Historical data is used for investigating incidents and trends from the past, as well as the verification of simulation results.

3.3 Initiative evaluation model

3.3.1 List cost saving initiatives

The high-level plant investigation provides a broad outline of all major processes and equipment. The next step is to compile a list of all applicable cost saving initiatives for the sinter plant under review. Possible cost savings initiatives for investigation can be identified by means of the following:

- Research cost saving initiatives identified for other similar sinter plant components in literature;
- Research energy saving initiatives to reduce the consumption of different energy sources on the sinter plant; and
- Gather inputs and ideas for cost saving initiatives from plant personnel.

From the literature review in Chapter 2, several cost saving initiatives were investigated. Initiatives with significant savings and short payback periods proved to be more favourable. Plant personnel are more eager to implement initiatives which yield immediate to short term results. The most feasible initiatives identified in Chapter 2 are:

- Sinter plant heat recovery;
- Oxygen and fuel enrichment;
- Segregated charging of materials;
- Sinter production scheduling;
- Automated sinter control;
- Optimising sinter bed properties;
- Reduction of air leakage; and
- Sinter quality optimisation.

These initiatives will be evaluated for implementation on the case study plant in Chapter 4.

3.3.2 Initiative rating function

Project ratings through evaluation methods proved to be the most popular method used in literature [57], [58]. Both evaluation methods were verified and validated and can therefore be considered to be trustworthy and reliable. The model developed in this study will also use an evaluation rating method to identify the most feasible initiatives to be implemented.

The model is developed to assist with the evaluation of sinter plant cost saving initiative investigations to identify and prioritise the most feasible cost saving initiatives for further investigation. A function, called the initiative rating function (*IR*) and similar to the prioritisation function as developed by Breytenbach in Section 2.4, will be developed.

The *IR* will also consist of two parts. The first part, called the multiplier prioritisation (*MP*), will be a sum of all the initiative multipliers that can be defined after the high-level investigation. The *MP* will be discussed in more detail in Section 3.3.3. The second part of the *IR* is called the barrier evaluation function (*BE*). The *BE* will be a sum of all the ratings of the different project barriers. The *BE* will be discussed in more detail in Section 3.3.4.

As with the function of Breytenbach, the *MP* and *BE* will also be multiplied to obtain an overall *IR*. The *IR* is then converted to be expressed in the form of a percentage as it seems more appealing. It requires an additional step where the achieved *IR* is divided by the maximum possible rating and finally multiplied by 100. The developed *IR* is displayed in Equation 5.

Equation 5: Initiative rating function

$$IR = \frac{MP \times BE}{IR_{Max}} \times 100$$

where *IR* represents initiative rating;
MP represents multiplier prioritisation; and
BE represents barrier evaluation;

with

Equation 6: IRMax

$$IR_{Max} = MP_{Max} \times BE_{Max}$$

where IR_{Max} represents maximum possible initiative rating.
MP_{Max} represents maximum multiplier prioritisation; and
BE_{Max} represents maximum barrier evaluation.

The MP_{Max} and BE_{Max} values will be explained in Section 3.3.3 and Section 3.3.4.

The *IR* should be completed for each cost saving initiative. All the initiatives will then be compared to determine the most feasible initiatives for further investigation.

3.3.3 Multiplier prioritisation

The *MP* forms the first part of the *IR*. The *MP* is the sum of four important investigation factors. These factors are selected for the *MP* as they can be determined without a very detailed high-level investigation. These four factors are:

- Previous implementation;
- Energy cost rating;
- Utilisation and availability; and
- Capital investment.

Previous implementation

Previous implementation is an important aspect when new initiatives are investigated. If an initiative is already implemented there is a smaller need for further investigation. In those cases, the investigation priority will be much lower, because in some cases, previous investigation or implementation was in the process but not fulfilled.

Energy cost rating

The energy cost rating represents the energy cost contribution towards the total energy cost of the energy consumption on the plant. The energy cost rating is high when the investigated equipment are large energy consumers or are responsible for high operational costs on the plant.

Utilisation and availability

Equipment with a high utilisation rate is frequently used during plant operations. Initiative investigations on equipment with high utilisation are more feasible. More savings are achieved when the operations are improved on equipment that is frequently in use.

Capital investment

More than 80% of the studies from the literature review showed that capital investment is amongst the leading barriers that restrict the implementation of new cost saving initiatives. For this reason, capital requirements will have a large influence on the prioritisation of an initiative.

Equation 7 displays the *MP*, with the incorporation of the abovementioned investigation factors.

Equation 7: Multiplier prioritisation function

$$MP = M_{PI} + M_{ECR} + M_U + M_C$$

where M_{PI} represents previous implementation;
M_{ECR} represents energy cost rating;
M_U represents utilisation and availability; and
M_C represents capital.

Schutte [58] developed a matrix to determine the value of project aspects. This matrix acted as a guideline to determine the values of project aspects without having to make any invalid assumptions. In the same way, a multiplier matrix will be developed to assist with assigning meaningful values to the four abovementioned factors. The matrix will be called the multiplier matrix.

The multiplier matrix will have an option range from 0 to 5. Each multiplier factor will have a different set of options. The rationale behind each set of options is provided in Table 5.

Table 5: Multiplier matrix options

Previous implementation		
5	No implementation or investigation	No previous initiatives like the one under investigation have been implemented or investigated. This maximise the potential to identify and implement cost saving initiatives in this section of the plant.
4	Previous investigation, positive attitude	A positive attitude towards a previous investigated initiative creates an opportunity to build and develop on previous studies. This reduce required effort as previous work can be reused.
3	Successful implementation, not sustained	Indicates that previous efforts could implement the project. Less effort is required as previous work can be reused. Additional effort will, however, be required to make the project sustainable.
2	Previous investigation, no implementation	Although previous work can be reused, reasons for failing to implement the project should be investigated before any further investigation should take place.
1	Previous investigation, negative attitude	A negative attitude towards a previous investigated initiative require additional efforts to convince plant personnel to again reinvestigate the project.
0	Successful implementation	Indicates that a successful project has already been successfully implemented. This minimise the potential to identify and implement cost saving initiatives in this section of the plant.

Energy cost rating		
5	Equipment energy cost > 10% of the total plant energy cost	Indicates that the energy costs of the component under investigation contributes to more than 10% of the total energy costs by the entire plant.
4	Equipment energy cost > 5% of the total plant energy cost	Indicates that the energy costs of the component under investigation contributes to between 5 and 10% of the total energy costs by the entire plant.
3	Equipment energy cost < 5% of the total plant energy cost	Indicates that the energy costs of the component under investigation contributes less than 5% of the total energy costs by the entire plant.
2-0	It can be difficult to determine the exact energy cost ratios for all the components. Therefore, less matrix options are provided to reduce the level of uncertainty when assigning values to the energy cost rating factor. The three possible options will range from 5 to 3 so that all three options still have a noticeable effect on the *MP*.	
Utilisation and availability		
5	Critical equipment, primary equipment with backup	Critical equipment is always used during operation. This means that energy savings on the critical equipment will always be present when the plant is in operation. The security of having backup equipment often allows more investigation opportunities.
4	Alternate between equipment regularly	Regular equipment alternation indicates energy savings on equipment will be present, regularly. Equipment alternations also allow opportunities to investigate individual component efficiencies.
3	Primary equipment without backup	Primary equipment is always used during operation. This means that energy savings on the primary equipment will always be present when the plant is in operation. Plant personnel may be more cautious with investigations on primary equipment without backup.
2	Equipment utilised once a day	Energy savings on the equipment are reduced to once a day when the equipment is in operation.
1	Equipment utilised once a week	Energy savings on the equipment are even more reduced to once a week when the equipment is in operation.

0	Equipment utilised only during maintenance	Secondary backup equipment is only used during maintenance when the primary equipment is out for maintenance. Implementing cost saving initiatives on secondary equipment will only realise savings when the primary equipment is out for maintenance.
Capital required		
-	It can be difficult to determine the exact amount of capital required to implement a project without any detailed investigation. Therefore, less matrix options are provided to reduce the level of uncertainty when assigning values to the capital investment factor.	
5	No capital required	Zero capital initiatives are the most favoured initiatives as cost savings can be realised with no capital requirements.
3	Low capital project	Low capital initiatives fall in this category. Although a capital amount is required, it is small enough to be covered by the operational budget of the plant. No large fund request applications are required. Therefore, the initiatives that fall in this category can get a maximum capital rating of 3.
1	High capital project	High capital initiatives fall in this category. Initiatives in this category require an extremely good business case with guaranteed savings to convince plant personnel. Capital to this extent is seldom available and cause initiatives in this case to be overlooked, most of the time. Therefore, the initiatives that fall in this category get a capital factor contribution of 1.

The developed multiplier matrix is displayed in Table 6. The *MP* is completed by obtaining the respective values for the four multiplier factors in this multiplier matrix.

The MP_{Max} value is obtained by substituting the maximum option value of 5 into each of the multiplier factors in Equation 8 to provide a maximum value of 20.

Equation 8: MP_{Max}

$$MP_{Max} = M_{PI} + M_{ER} + M_U + M_C$$

Table 6: Multiplier matrix

Multiplier matrix	**5**	**4**	**3**	**2**	**1**	**0**
Previous implementation (M_{PI}):	No implementation or investigation	Previous investigation, positive attitude	Successful implementation, not sustained	Previous investigation but no implementation	Previous investigation, negative attitude	Successful implementation
Energy cost ratio (M_{ECR}):	Equipment energy cost >10% of total plant energy cost	Equipment energy cost >5% of total plant energy cost	Equipment energy cost <5% of total plant energy cost			
Utilisation and availability (M_U):	Critical equipment, primary equipment with backup	Alternate between equipment regularly	Primary equipment without backup	Equipment utilised once a day	Equipment utilised once a week	Equipment utilised only during maintenance
Capital required (M_C):	No capital required		Low capital project		High capital project	

3.3.4 Barrier evaluation

The initiative evaluation function (*IE*) forms the second part of the *IR*. The *BE* consists of the sum of the remaining initiative investigation barriers that were mentioned in Chapter 2. These barriers were:

- Product quality;
- Payback period;
- Investigation effort;
- Implementation effort;
- Operational effort; and
- Sustainability.

The *BE* will combine the methods developed by Breytenbach [57] and Schutte [58]. Breytenbach proposed the second part of the function to be a sum of the total power and electricity rankings. Schutte's method introduces weights to actively influence the evaluation results.

Similarly, the *BE* consists of six barrier factor values that represent the barriers as mentioned above. An associated factor weight will be assigned to each barrier factor to obtain a similar influential effect as Schutte's method in the development of his evaluation model. With this approach, the initiative evaluation results can improve the prioritisation of more feasible initiatives.

The *BE* is displayed in Equation 9. The six barrier factor values are multiplied by each associated barrier factor weight (w). The six multiplied barrier factors are then summed to obtain the value of *BE*.

Equation 9: Barrier evaluation function

$$BE = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Sus}$$

where Q_s represents sinter quality;
P_{PP} represents the payback period;
E_{op} represents the operational effort;
E_{im} represents the implementation effort;
E_{in} represents the investigation effort; and
S_{Sus} represents the sustainability.

The *w's* represent the barrier factor weight for each associated barrier. These weights range between 1 and 5, with 5 being the most important and 1 the least important. The values of the weights are ranked according to their importance and relevance as seen from literature.

Sinter quality

Sinter quality involves the production concerns and reliability barriers as mentioned in Section 2.5. According to Section 2.5 , both Hamer [60] and Lidbetter [52] highlighted the importance of product quality and that it is considered as a very important business factor. Ensuring good product quality will, therefore, be considered as one of most important barriers. As a result, a barrier weight of 5 will be assigned to the sinter quality barrier.

Payback period

The payback period of the project entails the time it takes for a project to recover the initial capital outlay in terms of savings. Equation 10 shows the calculation to determine the payback period of a project. Plant personnel consider a shorter payback period as less inconvenient as they see the benefits of the project sooner.

The studies of Mac Nulty [61], Santana and Bajay [62], García-Quevedo *et al*. [64] and Roychaudhuri *et al*. [65] all state that project capital and payback periods are considered as the most important project barriers. The critical situation in the steel industry places further restrictions on the funding of new capital projects. Capital restrictions encourage cost saving initiatives with no capital requirements and short payback periods. The payback period barrier is therefore considered to be the most important and will receive a barrier weight of 5.

Equation 10: Payback period

$$Payback\ period\ (y) = \frac{Project\ capital\ investment\ (R)}{Annual\ project\ saving\ \ (\frac{R}{y})}$$

Operational effort

Operational effort is the ease of utilising the new implementation or equipment. It involves limited staff time, information and inconvenience barriers as mentioned in Section 2.5. Additional operational effort is often required after new installations. Large amounts of additional information may seem challenging to operators and staff members should be trained to use the new systems.

Experienced staff members may be resistant to change and experience new systems as inconvenient. Maintenance schedules would have to be adapted to accommodate newly installed equipment. The operational effort form part of the continuous cycle throughout the project lifetime and therefore a barrier weight of 3 is assigned.

Implementation effort

Installation or implementation of the project involves limited capital, limited staff time, production concerns and inconvenience barriers mentioned in Section 2.5. New equipment installations require additional time and expertise. High-level expertise is not always available amongst plant personnel in which case external experts must be contracted to support new project installations.

Hiring external contractors can be expensive and additional time is required for contractor management. Hosting contractors on site poses new safety and security risks which are governed by additional regulations. This may cause inconvenience to plant personnel.

Continuous production operations with limited downtime at most steel production plants may cause resistance from production staff to implement new projects. The project implementation barrier is therefore considered to be more important than the investigation effort barrier.

The implementation phase of projects is a once-off occurrence in the project lifetime therefore a barrier weight of 2 is assigned to the implementation effort barrier.

Investigation effort

The investigation process for a new project may be time-consuming. If there are no subject matter experts available amongst plant personnel to assist with the investigation process, a significant amount of additional time must be dedicated to conduct a detailed investigation. In certain cases, limited knowledge would require inputs from external energy savings companies.

Investigation effort involves limited staff time, production concerns and information barriers mentioned in Section 2.5. System information may be limited and plant specific. If certain process measurements required for project investigation are not captured for the specific plant, additional meters will have to be installed.

Personal experience with project investigations indicated that investigation effort barriers can easily be overcome. Complex systems are simplified and the necessary assumptions are made where measurements are not available. The weight for the investigation effort barrier is therefore amongst the smallest weights with a value of 1.

Sustainability

Sustainability entails the amount of effort required to maintain the new system and involves the inconvenience barrier mentioned in Section 2.5. New systems should be easy to maintain. Additional maintenance effort on the new system should be minimised to ensure that the system will not be neglected within a short period after commissioning.

However, Silvius *et al.* [66] investigated 12 project perspectives from different industries. Their studies indicated that although project sustainability is important, the respondents from their study considered project sustainability amongst the lowest priorities during project investigations. The minimum barrier weight of 1 is therefore assigned for sustainability.

Table 7 provides a summary of the values assigned to each barrier weight.

Table 7: Barrier weights

Barrier	Symbol	Weight
Sinter quality	w_{SQ}	5
Payback period	w_{PP}	5
Operational effort	w_{op}	3
Implementation effort	w_{im}	2
Investigation effort	w_{in}	1
Sustainability	w_{sus}	1

Another matrix, called the barrier matrix will be developed to assist with the assignment of meaningful values for each barrier factor. The barrier matrix will have a set of five options that can be selected for each barrier. Each initiative barrier rating is multiplied with the corresponding barrier weight to contribute a certain weight towards the *BE* function. In Table 9 the developed barrier matrix is shown.

As mentioned in Section 2.5 and earlier in this section, sinter quality is one of the most important barriers. Production personnel will be unwilling to implement any initiatives that will have a negative effect on the sinter quality. These initiatives will only be investigated if it is justified by a large savings margin. The five sinter quality barrier options will, therefore, range between 2 and -2.

A negative barrier factor will greatly reduce the *IR* for the specific initiative. The five remaining barrier factors will have a set of five available options that range between 0 and 4. The rationale behind each set of options is provided in Table 8.

Table 8: Barrier matrix options

Sinter quality		
2	Large improvement on sinter quality	The literature review showed that improvements on sinter quality can lead to significant savings at the downstream processes. Large improvements on sinter quality are therefore regarded as top priority initiatives. Large improvements imply that the initiative will add new or replace raw materials to the sinter mixture that will have a large positive effect on the sinter quality.
1	Small improvement on sinter quality	Small improvements imply that the initiative will adjust the present sinter mixture to have a small improvement on sinter quality.

0	Does not affect the sinter quality	This implies that the initiative will not affect the sinter quality.
-1	Slight reduction in sinter quality	Any initiative that reduces the sinter quality will need to be justified. A reduction in sinter quality may cause inefficient operations downstream.
-2	Large reduction in sinter quality	Any initiative that reduces the sinter quality will need to be justified. A large reduction in sinter quality may cause more inefficient operations that lead to much more energy costs downstream. Initiatives in this category are, therefore, regarded as the lowest priority initiatives.
	Payback period	
4	< 3 Months	Initiatives with a short payback period are top priority, as the savings overtake the capital investment within the first three months.
3	< 6 Months	Savings overtake the capital investment within six months.
2	< 12 Months	Savings overtake the capital investment within 12 months.
1	< 24 Months	Savings overtake the capital investment within 24 months.
0	> 24 Months	These initiatives are very low priority as the savings margin is too small and the savings benefit of the initiative is only experienced after two years of implementation.
	Operational effort	
4	No new operational skills or operational effort required.	Initiatives that require no new operational skills are regarded as high priority initiatives. Operators can continue with the plant operations as they did before the initiative implementation. No additional operational efforts are added with the new initiative.
3	New operations require minimum new skills, but no additional effort.	Small adjustments to the standard operating procedures are required. Operators will be able to follow adjusted operating procedures with ease. No additional operational efforts are added with the new initiative.
2	New operations require new skills and additional operational efforts.	A new set of standard operating procedures are implemented. Operators require new skills, but will be able to follow operating procedures with ease. Small amount of

		additional operational efforts are required with the new initiative.
1	New implementation requires experienced operational skills and additional operational efforts.	New implementations in this category require experienced operators to actively monitor and control the system in the initial operating phase. Once they are trusted with the new system will they be able to train less experienced operators. Additional operational and maintenance efforts are required with the new initiative.
0	Entire new system. Operators should be sent for specialised training.	Initiatives in this category are the lowest priority as significant amounts of additional operational time and training costs are required. Entire new and complex systems that involves health, safety and environmental requirements are installed. All operators require specialised and skilled training to be able to operate the new system.
Implementation effort		
4	No installation required. Only operational or scheduling adjustments required for implementation.	Initiatives that require no new equipment installations or equipment adjustments are regarded as high priority initiatives, as no additional costs or personnel is required for implementation.
3	Installation/implementation possible within two hours. Installation can take place during normal operation.	Implementation is quick and easy. Only small adjustments required on the system. Initiatives in this category are still high priority as the initiative can be implemented without any inconvenience.
2	Installation can be done with only small operational adjustments within 24 hours.	Implementation is completed within approximately two shifts. Downtime is restricted to minimum. Only small adjustments on the system are required.
1	Installation takes place within a month. Significant operational adjustments should be made.	Implementation is completed within one month. The plant experiences a downtime period during implementation. New systems and equipment are installed.

0	Implementation extends to more than a month. Major operational adjustments should be made.	Implementation extends to more than a month. The plant is shut down during implementation. Qualified and trained personnel are required for implementation. New systems and equipment are installed.
Investigation effort		
4	Minimal investigation required. All required data is available for investigations.	Initiatives that require minimum investigation effort are regarded as the higher priority initiatives. Initiative investigation is simple and easy and can be completed within a month. All the required data and measurements are available for the investigation.
3	Minimal investigation required. Most of the required data is available for investigations.	Initiative investigation is simple and easy. Initiative investigation can be completed within a month. Most of the required data and measurements are available for the investigation. Only a few assumptions need to be made.
2	Fair amount of investigation required. Most of the required data is available for investigations.	Initiative investigation can be completed within two months. Most of the required data and measurements are available for the investigation. Only a few assumptions need to be made.
1	Significant amount of investigation required. Most of the required data is available for investigations.	Skilled and qualified personnel is required for an accurate investigation. Initiative investigation can be completed within three months. Most of the required data and measurements are available for the investigation.
0	High level of knowledge for investigation required. Additional devices are required to measure required data.	Investigation experts in the field are required for an accurate investigation. Available data is very limited. Additional measurement equipment should be installed to obtain required investigation data. Initiatives in this category are the lowest priority, as additional investigation costs and fees will be required for investigation.

Sustainability		
4	No maintenance is required. System is adjusted permanently.	Initiatives that are easily sustainable are regarded as high priority. Initiatives in this category require no additional maintenance or efforts to ensure that the initiatives continue.
3	Operation seldom requires maintenance. Optimised operations are easy to sustain.	Initiatives rarely require any additional maintenance. Initiatives requiring minimal efforts are dedicated to ensure that the initiatives continue.
2	Small amounts of maintenance required on a regular basis. Optimised operations are sustainable with little effort.	Little additional maintenance effort is added to the present maintenance schedule to maintain the initiative on a regular basis. New initiative operations are sustained with little extra effort.
1	Maintenance required on a regular basis. Optimised operations are sustainable with descent effort.	Additional maintenance effort is added to the present maintenance schedule to maintain the initiative on a regular basis. New initiative operations can be sustained, but will require additional effort.
0	High level maintenance is required. Intense efforts are required for sustainability.	Initiative require high level knowledge and sometimes even plant downtime to be maintained are regarded as lowest priority. New initiatives are almost impossible to be sustained.

The developed barrier matrix is displayed in Table 9. The respective values for the six barrier factors are obtained from the barrier matrix. The *BE* is then completed by adding all six barrier factors after they have been multiplied by the corresponding barrier weight.

The BE_{Max} value (Equation 11) is obtained by substituting the maximum option value of 4 into each of the barrier factors and the barrier weights as indicated in Table 7. The value of the $\mathrm{BE}_{\mathrm{Max}}$ is 68.

Equation 11: BE_{Max}

$$BE_{Max} = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Sus}$$

Table 9: Barrier matrix

Barrier matrix	2	1	0	-1	-2
Product quality (Q_S):	Large improvement on sinter quality.	Small improvement on sinter quality.	Does not affect the sinter quality.	Slight reduction in sinter quality.	Large reduction in sinter quality.
	4	3	2	1	0
Payback period (P_{PP}):	< 3 months	< 6 months	< 12 months	< 24 months	> 24 months
Operational effort (E_{op}):	No new operational skills required.	New operations require minimum new skills, but no additional effort.	New operations require new skills and additional operational efforts.	New implementation requires experienced operational skills.	Entire new system. Operators should be sent for specialised training.
Installation/implementation effort (E_{im}):	No installation required. Only operational or scheduling adjustments required for implementation.	Installation/implementation possible within 2 hours. Installation can take place during normal operation.	Installation can be done with only small operational adjustments within 24 hours.	Installation takes place within a month. Significant operational adjustments should be made.	Implementation extends to more than a month. Major operational adjustments should be made.
Investigation effort (E_{in}):	Minimal investigation required. All required data is available for investigations.	Minimal investigation required. Most of the required data is available for investigations.	Fair amount of investigation required. Most of the required data is available for investigations.	Significant amount of investigation required. Most of the required data is available for investigations.	High level of knowledge for investigation required. Additional devices are required to measure required data.
Sustainability (S_{sus}):	No maintenance is required. System is adjusted permanently.	Operation seldom requires maintenance. Optimised operations are easy to sustain.	Small amounts of maintenance required on a regular basis. Optimised operations are sustainable with little effort.	Maintenance required on a regular basis. Optimised operations are sustainable with descent effort.	High level maintenance is required. Intense efforts are required for sustainability.

3.4 Detailed investigation

3.4.1 Preface

The purpose of the detailed investigation is to determine if the initiatives that were highlighted from the developed initiative evaluation model are possible and feasible for implementation. Figure 16 displays the detailed investigation process.

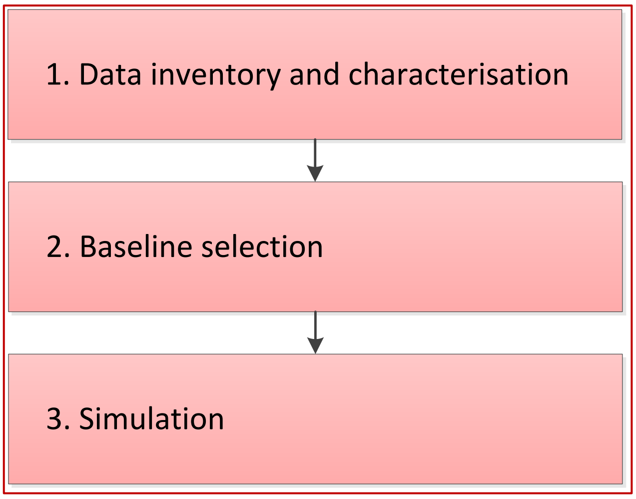

Figure 16: Detailed investigation process

3.4.2 Data inventory and characterisation

Data inventory

Information and data sheets from the high-level plant investigation need to be revisited. Data sheets and plant layouts should be updated with the latest information. Multiple data measurements from various sources are used as check meters. More available data sources will improve the accuracy of the measurements and conflicting measurements can be addressed.

After completion of the initiative evaluations, the most feasible cost saving initiatives will be highlighted for further investigation. Specific data sets with more details on plant equipment or processes under consideration should be gathered where possible. Figure 17 displays an updated version of the PFD of a typical sinter plant.

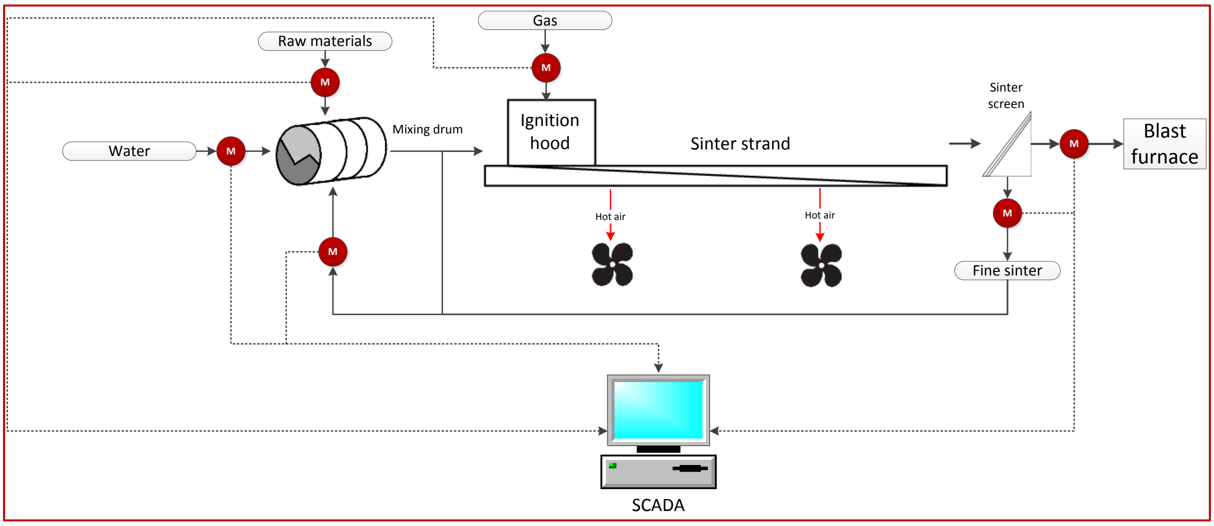

Figure 17: Example of updated PFD

Characterisation

On most typical processing plants, production is the main energy driver. This implies that the energy consumption is directly related to the production of the plant. If the production of the plant can be forecasted, it should also be possible to forecast the energy consumption of the plant.

Production trends can be used to characterise the plant's production. The maximum production capacity and production performance under different operational conditions should be determined from the production trends. This will allow improved production forecasting. Similarly, the energy consumption can be characterised from the energy consumption trends.

An example of an energy consumption (GJ) against plant production (tonnes) scatter plot of a typical sinter plant is provided in Figure 18. This scatter plot can be utilised to characterise the specific plant for energy intensity and maximum production.

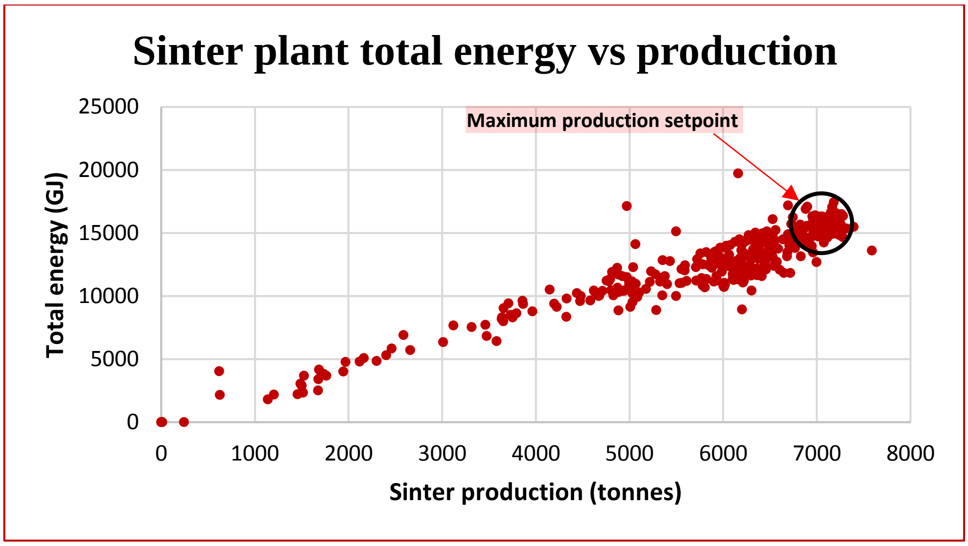

Figure 18: Characterisation scatter plot

Equipment availability and reliability also play a large part in the characterisation of the plant. It is important to know the actual performance capabilities for each component. The actual overall plant production, availability and reliability can be calculated using the following equations [60]:

Equation 12: Production capacity

$$Production\ capacity = R_{eff} \times E_{Av} \times Calender\ hours$$

where R_{eff} represents effective production rate; and
E_{Av} represents equipment availability;

with

Equation 13: Effective production rate

$$R_{eff} = R_{emp} \times E_{Re}$$

where R_{emp} represents empirically calculated production rate; and
E_{Re} represents equipment reliability;

with

Equation 14: Equipment reliability

$$E_{Re} = 1 - \frac{Unplanned\ stoppage\ hours}{calendar\ hours}$$

and

Equation 15: Equipment availability

$$E_{Av} = 1 - \frac{Planned\ maintenance\ hours}{calendar\ hours}$$

3.4.3 Baseline selection

The purpose of the baseline is to determine the plant performance before any project interventions. The plant performance after implementing the initiative will then be compared with the baseline and any improvements against the baseline will be regarded as savings. All investigated initiatives can be divided into one of three different categories, namely energy efficiency, load shift and peak clip initiatives.

Energy efficiency initiatives involve the reduction in energy consumption while performing the same processes. Load shift initiatives are energy neutral initiatives where the load during expensive TOU periods is reduced by moving the load to less expensive periods. Peak clip initiatives involve the reduction in energy consumption during specific time periods where energy is more expensive [46].

In Section 2.4 it was noted that different initiative types require different baseline methods. Regression model baselines and profile baselines will be described in this study. Figure 19 displays the typical selection process for the preferred baseline methods for the different types of initiatives.

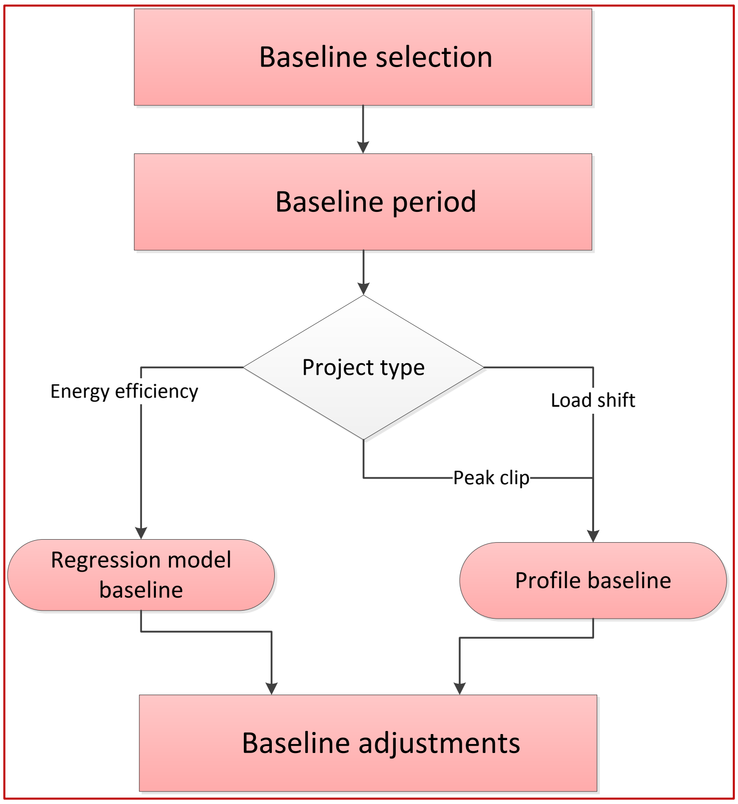

Figure 19: Baseline selection diagram

Baseline period

The baseline period indicates the period before the project interventions were implemented. A minimum baseline period of three months is considered and the baseline should be a true representation of normal operations. Wherever possible, sufficient baseline results are required to calculate the savings introduced by cost saving initiatives [60], [67].

In certain cases, the baseline should meet a specific criterion. Environmental changes such as winter and summer periods may also influence system performance. It is therefore required to select a baseline which accommodates environmental changes which influence system performance [60], [67].

Regression model baseline

Energy efficiency initiatives were noted to be successfully baselined utilising regression model baselines. Regression baselines are used where energy consumption is measured against specific energy drivers. In most cases production is the main energy driver but it could also be any other important system parameter with a dependence on a specific energy source.

Regression baselines require regression evaluations to determine the accuracy of the baseline. The R-squared correlation coefficient (Equation 16) is called the coefficient of determination. It is utilised to judge the adequacy of the regression between the energy driver data and the energy source data. R-squared is often referred to as the amount of variability in the data explained or accounted for by the regression model [67].

Equation 16: R-squared

$$r^2 = \left(\frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{x_i-\bar{x}}{s_x}\right)\left(\frac{y_i-\bar{y}}{s_y}\right)\right)^2$$

where n is the number of data points;
x_i is the value on the x-axis for the i^{th} data point;
y_i is the value on the y-axis for the i^{th} data point;
$\bar{x}$ is the mean value of the x-values of all the data points;
$\bar{y}$ is the mean value of the y-values of all the data points;
s_x is the standard deviation of the x-values of all the data points; and
s_y is the standard deviation of the y-values of all the data points.

For a valid regression baseline, a strong correlation between the data points should be attained. Figure 20 provides an example of a strong correlation between data points as well as the R-squared value. This implies a strong relationship between the production (*x*-axis) and the total energy (*y*-axis).

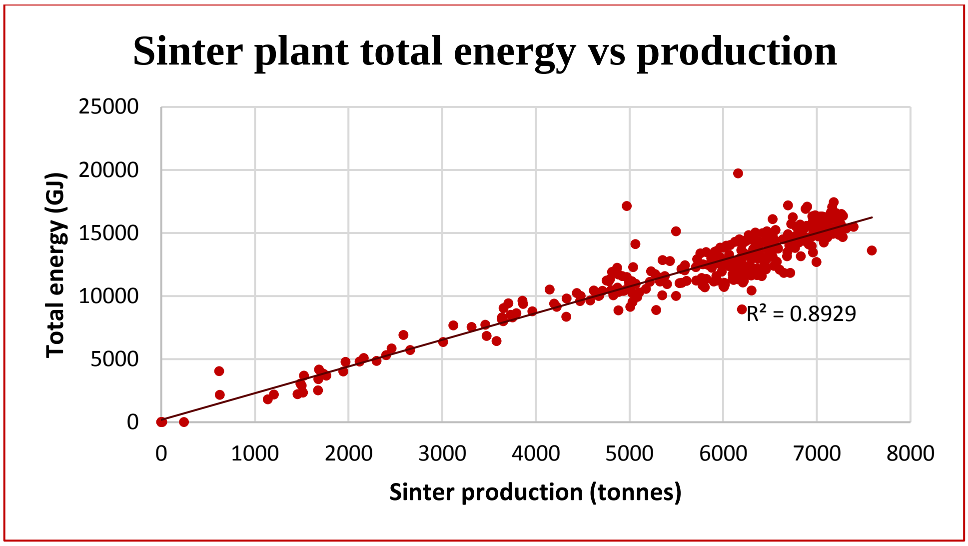

Figure 20: Sinter plant energy consumption vs production regression baseline

Profile baselines

Load shift and peak clip initiatives were noted to be sufficiently baselined by means of profile baselines. Data intervals are important when utilising profile baselines. The resolution should be small enough to capture all operational incidents. Important system parameters are closely monitored in most cases and will maintain real-time, high-resolution data readings.

Less important parameters or base load parameters have lower resolution data readings. These readings are mainly used for daily or weekly monitoring. Figure 21 provides an example of a high-resolution profile baseline over a 7-day period.

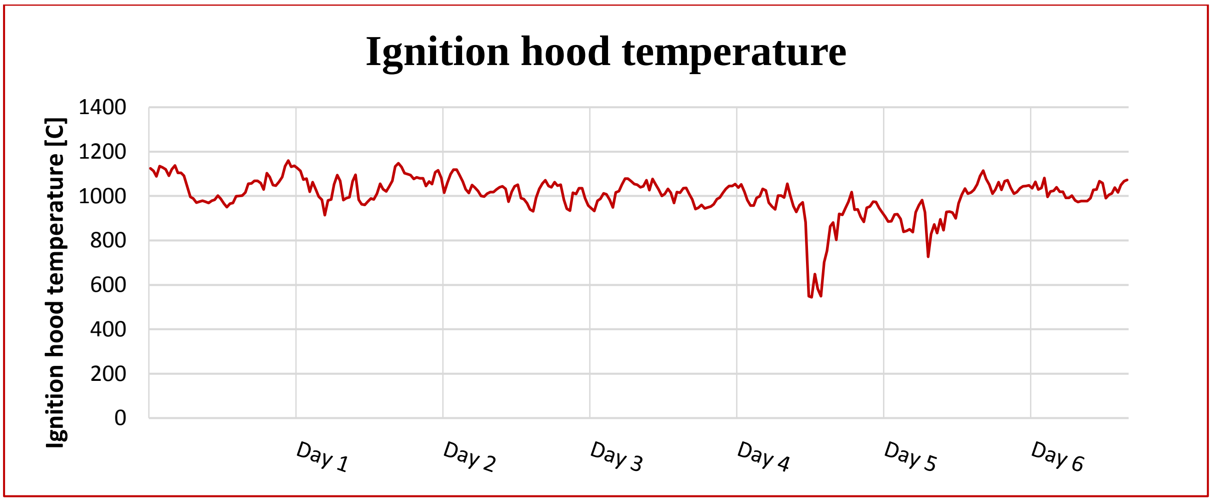

Figure 21: High-resolution profile baseline

Figure 22 contains an example of a low-resolution profile baseline of the daily sinter production over a period of one month.

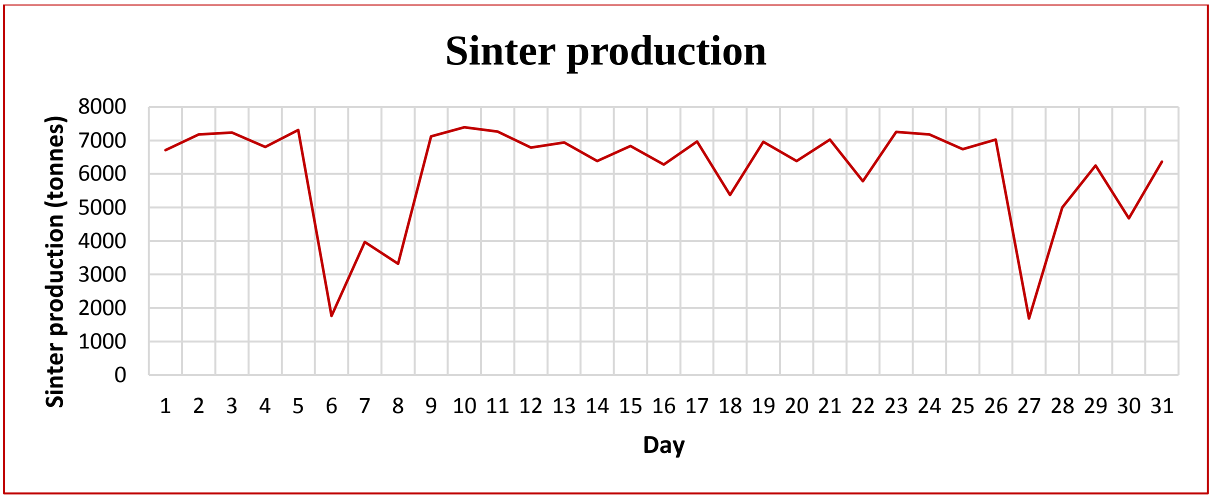

Figure 22: Month profile baseline in daily resolution

Baseline adjustments

Baseline adjustments are made to compensate for energy driver increases or decreases. Energy drivers are not always constant and fluctuate depending on operational circumstances. It is therefore understandable that whenever production parameters are changed in relation to those used for establishing the baseline, energy consumption will change accordingly [67]. Typical baseline adjustments are baseline scaling. Equation 17 displays the baseline scaling equation to be used.

Equation 17: Baseline scaling[9]

$$SB = OB \times \frac{Calculated\ energy\ driver\ value}{Baseline\ energy\ driver\ value}$$

where *SB* represents scaled baseline; and
OB represents original baseline;

3.4.4 Simulation

The initiative evaluation process should be done prior to the development of the simulation. This is necessary to identify the most feasible initiative for further investigation through means of a simulation.

Simulations are developed to assist with the operational predictions on the system. Before a cost savings project can be implemented, the project is simulated to predict the behaviour of the intervention after implementation. As an unlimited number of possible initiatives and associated simulations options exist it is impossible to describe all possible simulation alternatives.

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[9] Baseline scaling equation adapted from Booysen, [67].

A generic simulation process similar to that utilised by Zeelie [59] and Hamer [60] was developed in Microsoft Excel. Figure 23 provides a diagrammatic representation of the simulation process that was utilised throughout this study.

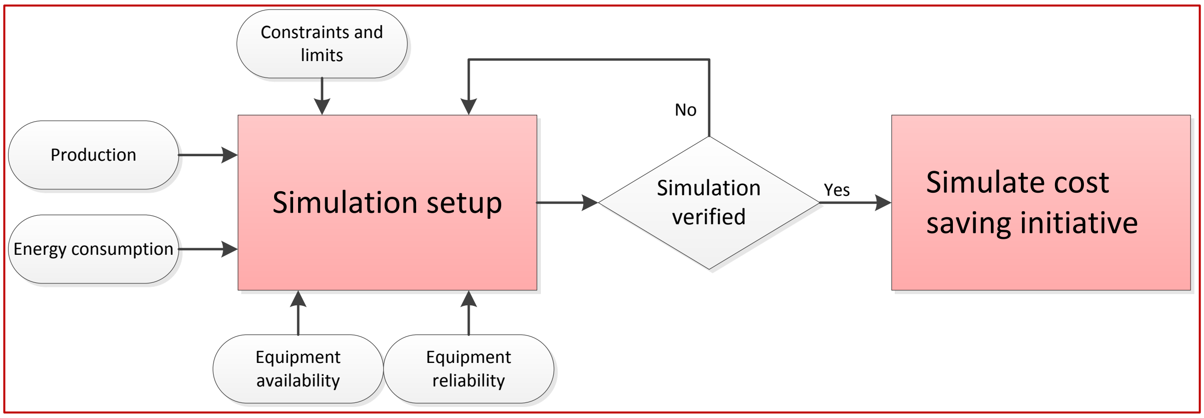


Figure 23: Simulation process

The initial step in simulation is to mimic the actual performance of the plant. Several inputs are provided to the simulation during the initial setup. Production rates and energy consumption are the two most significant input values for the simulation. These values are required for determining the plant's baseline energy intensity.

Constraints and limits are boundaries that are set to restrict the simulation outcomes and represent actual performance capabilities of the plant. Typical constraints include temperature limits, strand speeds and stock levels. Assumptions and predictions are utilised in the absence of actual measurements. Equipment failures and maintenance requirements during plant operations cause plant imperfections. Equipment availability and reliability inputs incorporate such equipment failures and maintenance requirements.

The next important step is to calibrate and verify the simulation. Simulation calibration is required to enable the provision of accurate results. Measured inputs are entered into the simulation so that it can be calibrated to provide similar results to the actual measured outputs. The simulation is verified if a new dataset entered into the simulation renders similar results as the actual measured output of the new dataset. New inputs representing the implementation of the cost savings initiative are entered into the simulation. The simulation results are then analysed to determine the effect of the new cost saving initiative on the system.

Project implementation may only commence once all previous steps of the cost saving opportunity identification process were completed and the results indicate significant potential for cost savings. As implementation steps may vary from one plant to the next, certain plants might require pilot studies before final and permanent implementation. Pilot studies provide concrete results from a temporary implementation in the production environment. Final implementation decisions are based upon the results obtained during the pilot studies. In the event where no pilot studies are required, immediate production implementation may commence after executive approval.

3.5 Conclusion

This study provides a new methodology for the evaluation of cost saving initiatives. Important barriers identified by literature were utilised in the development of the evaluation model. The initiative evaluation model provides an *IR* value consisting of the product of two functions, a *MP* and *BE*.

The MP provides a priority evaluation based on a high-level plant investigation. The *BE* evaluates the remaining barriers that are experienced by the investigated cost saving initiative during a more specific plant investigation. The final step of the methodology explains the process to perform detailed investigations to support implementation decisions.

4. Practical application and results

This chapter describes the practical application of the initiative evaluation model on a case study sinter plant. The initiative evaluation results highlighted a feasible initiative for implementation.

4.1 Preamble

The proposed cost saving initiative evaluation model was applied to the sinter plant of a steel manufacturing facility in South Africa. For confidentiality purposes, the sinter plant will be referred to as Sinter Plant A. A plant investigation was performed on Sinter Plant A to enable the use of the initiative evaluation model for the identification of feasible cost saving initiatives.

A detailed investigation was performed on the most feasible initiative identified by the developed model, utilising baseline analysis and extensive simulation. Pilot studies were conducted to verify the actual effectiveness and possibility of the performance improvement initiatives before final implementation.

The values utilised for the simulation and those attained during the pilot studies are provided throughout this chapter. The simulation results and predictions are verified with the data obtained during the pilot studies. The cost savings resulting from the implemented energy saving initiative are calculated by comparing the current performance with the baseline performance that was established before the intervention.

4.2 Plant investigation and overview

4.2.1 Preface

The high-level plant investigation is the initial step of the project evaluation. During this step all the available information, data, drawings, layouts and PFDs are obtained. All the attained details and information will assist to make informed decisions during evaluation and detailed investigations.

4.2.2 Plant drawings

The plant drawing for Sinter plant A is shown in Figure 24. Valuable plant information and design specifications such as process flow, flow rates and large equipment were obtained from the drawing.

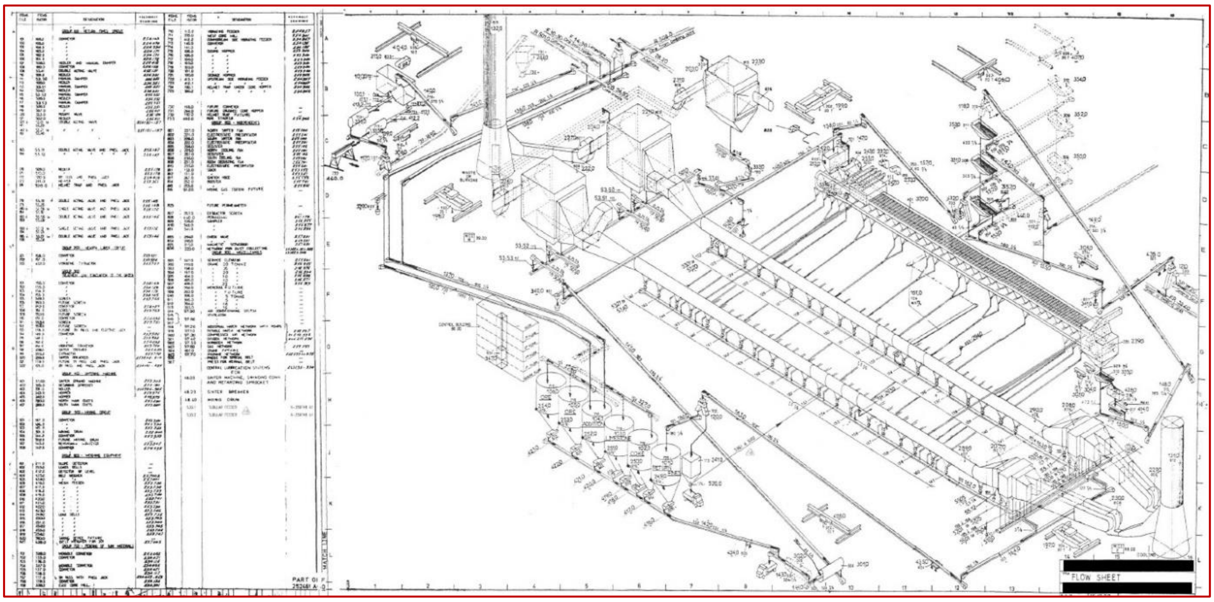


Figure 24: Plant drawing of Sinter plant A

4.2.3 SCADA system screen captures

Available system measurements and data trends were obtained from the Supervisory Control and Data Acquisition (SCADA) system. Raw material flow rates, ignition hood temperature and production rates are among the available measurements. An example of a SCADA system screen capture for Sinter plant A is displayed in Figure 25.

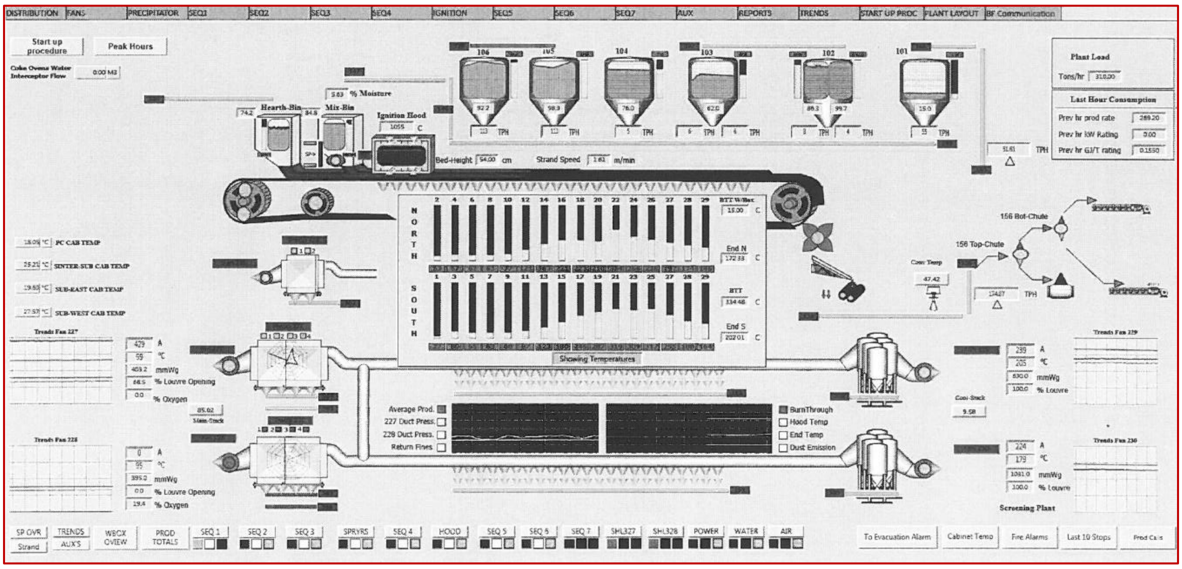


Figure 25: SCADA system screen capture of Sinter plant A

4.2.4 Production capacity

Sinter plant A is a sinter plant on a steel production facility in South Africa and was designed to produce sinter at a maximum production rate of 7200 t/d. It consists of a single 80 m x 4.5 m sinter strand.

The raw material feeder is configured to spread the sinter mix such that a sinter bed thickness of between 370 mm to 600 mm is maintained, depending on the required production rate.

The steel production facility utilises a single *BF* supplied with sinter from Sinter plant A and a single sinter strand. The maximum sinter consumption at the *BF* is approximately 6400 t/d with average consumption ranging between 5200 t/d and 5500 t/d. Surplus sinter is sent to the stock pile. Stock piles are maintained at levels ranging between 15 000 and 32 000 tonnes.

Sinter is crushed into smaller sinter cakes at the end of the sintering strand. The crushed sinter cakes are screened and those with sizes ranging between 5 mm and 45 mm are transported to the *BF*. Remaining sinter is transported back to the pre-sintered pile at a rate of approximately 70 t/h. This sinter is used to prepare the new 50 mm pre-sintered layer on the sinter strand.

Sinter Plant A utilises two 4.5 MW sintering fans and two 3.3 MW cooling fans for drafting air through the sinter bed and assist the combustion process. Sinter production can be slowed down by stopping any one of the four fans and reducing strand speed. This approach was appropriately dubbed 3-fan operation. During 3-fan operation, the *FFS* is reduced as the air flow is reduced. Table 10 provides the different production rates for the different fan configurations as reported by plant personnel.

Table 10: Sinter production rates with different fan configurations

Fan configuration	**Hourly production rate (tonnes)**	**Daily production rate (tonnes)**
4 Fans, 2 sinter and 2 cooling	280	6800-7200
2 Sinter fans and 1 cooling fan	240	5800-6200
1 Sinter fan and 2 cooling fans	200	4800-5200

4.2.5 Energy consumption

Although the total electrical load of the fans decreases during 3-fan operation, the individual electrical loads of the remaining three fans increase, thereby the nett saving cannot be directly proportioned to the saving obtained by stopping a single fan.

Raw materials including fine coke, anthracite, iron ore, limestone, and dolomite are mixed together in the raw material mixing drum. Water with a flow rate of 26 t/h is used to wet the mixture in the mixing drum. The moisture content of the raw materials is set to approximately 5.8% to ensure the correct granule size and burn through.

Fine coke and anthracite in the mixture act as fuel and constitute approximately 5% of the sinter mixture. Iron ore constitutes approximately 90% of the sinter mixture. The remaining 5% consists of limestone and dolomite which assist with the slag formation in the *BF*.

COG with a Wobbe Index of approximately 17.3 MJ/m^3, is burned in the ignition hood to generate the required heat for coke ignition. Ignition hood temperatures range between 1100°C and 1300°C. During low or no production periods, the furnace idles at a temperature of 900°C to protect the refractories inside the ignition hood.

An 8-hour planned maintenance is scheduled for every third Wednesday and the entire plant is shut down during these maintenance slots.

4.3 Cost saving initiative evaluation

4.3.1 Preface

Different cost saving initiatives were identified in the literature study in covered in Chapter 2. The method development discussion in Chapter 3 mentions a list of the most appealing initiatives that can be implemented on sinter plants. The feasibility of each of these initiatives will now be investigated for implementation on Sinter plant A.

This chapter will only provide the detailed process for performing the cost saving initiative evaluation for the Sinter plant A heat recovery cost saving initiative. The cost saving evaluations for the various other initiatives are provided in Appendix A.

4.3.2 Sinter plant heat recovery

Initiative description

Large amounts of heat are lost through the exhaust gas line at the ignition hood of Sinter plant A. An initiative to install a heat recovery system for recovering some of the heat from the off-gas line is investigated. The system will utilise recovered heat to preheat the combustion air supply to the ignition hood.

This can be achieved by replacing the single ignition hood exhaust gas line with several smaller exhaust gas lines which are diverted back to the combustion air inlet in a counter flow configuration. This will enable the exchange of large amounts excess heat between the exhaust gas lines and the combustion air feed towards the ignition hood. The increased combustion air temperature would imply a reduced demand for *COG* combustion for maintaining the temperature in the ignition hood.

Initiative evaluation

The initial step of the evaluation process is to complete the *MP*, described in Section 3.3.3 and previously stated with Equation 7.

Equation 7
$$MP = M_{PI} + M_{ER} + M_U + M_C$$

The high-level multiplier values were based on actual results and discussions during the high-level plant investigation. Table 11 provides the ratings and motivations for each high-level multiplier value.

Table 11: Sinter plant heat recovery high-level multiplier values

Barrier	Rating	Motivation
Previous implementation (M_{PI})	1	Sinter plant heat recovery was previously investigated to be installed on ignition hood off-gas line. A negative attitude towards the project as the project funds request application was turned down during the previous investigation.
Energy cost ratio (M_{ECR})	5	Several heat sources are available on the sinter plant. Heat recovery can be implemented on all energy sources present at the sinter plant, except electricity.
Utilisation and availability (M_U)	5	Heat will always be present on the sinter plant when the plant is in operation.
Capital required (M_C)	1	From literature, capital investment for heat recovery for this plant is approximately R450 000. Only capital projects less than R100 000 can be funded using the plant's own operational budgets. Sinter plant heat recovery initiatives are therefore, regarded as high capital projects.

Equation 3 yielded an *MP* value of 12 for the sinter plant heat recovery initiative after substituting the high-level multiplier values provided in Table 11 into Equation 7.

The next step was to calculate the *BE*, described in Section 3.3.4 and previously stated with Equation 9.

Equation 9
$$BE = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Sus}$$

Following a high-level investigation of the plant layout, process flow and data inventory, the various barriers were rated. These ratings and the associated motivations for each are provided in Table 12.

Table 12: Sinter plant heat recovery barrier ratings

Barrier	Rating	Motivation
Product quality (Q_S)	0	Sinter quality is not affected as the recovered heat will be sourced from off-gases after combustion.
Payback period (P_{PP})	0	It is shown from literature that the payback period is approximately 2.8 years.
Operational effort (E_{op})	2	Heat recovery on off-gas will not influence the present operations. New skills will only be required to utilise and monitor the heated air or water for steam or electricity generation.
Implementation effort (E_{im})	1	Heat recovery systems require large space to be installed. New pipe lines to contain the heated fluid should be installed and connected to the present system.
Investigation effort (E_{in})	3	Although temperature sensors are available in the ignition hood, no gas sensors or gas flow meters are available on the exhaust gas line. The necessary gas flow meters should be installed to quantify the amount of heat available for recovery.
Sustainability (S_{Sus})	2	Small amounts of additional maintenance to backwash and clean the heat exchangers will be required to ensure that effective heat exchange can take place. New operations are easy to be added to the normal everyday routines.

Table 13 provides the various barrier weights values. The motivation for each of these weightings were provided in Section 3.3.4.

Table 13: Reviewed barrier weights

Barrier	**Symbol**	**Weight**
Sinter quality	w_{SQ}	5
Payback period	w_{PP}	5
Operational effort	w_{op}	3
Implementation effort	w_{im}	2
Investigation effort	w_{in}	1
Sustainability	w_{sus}	1

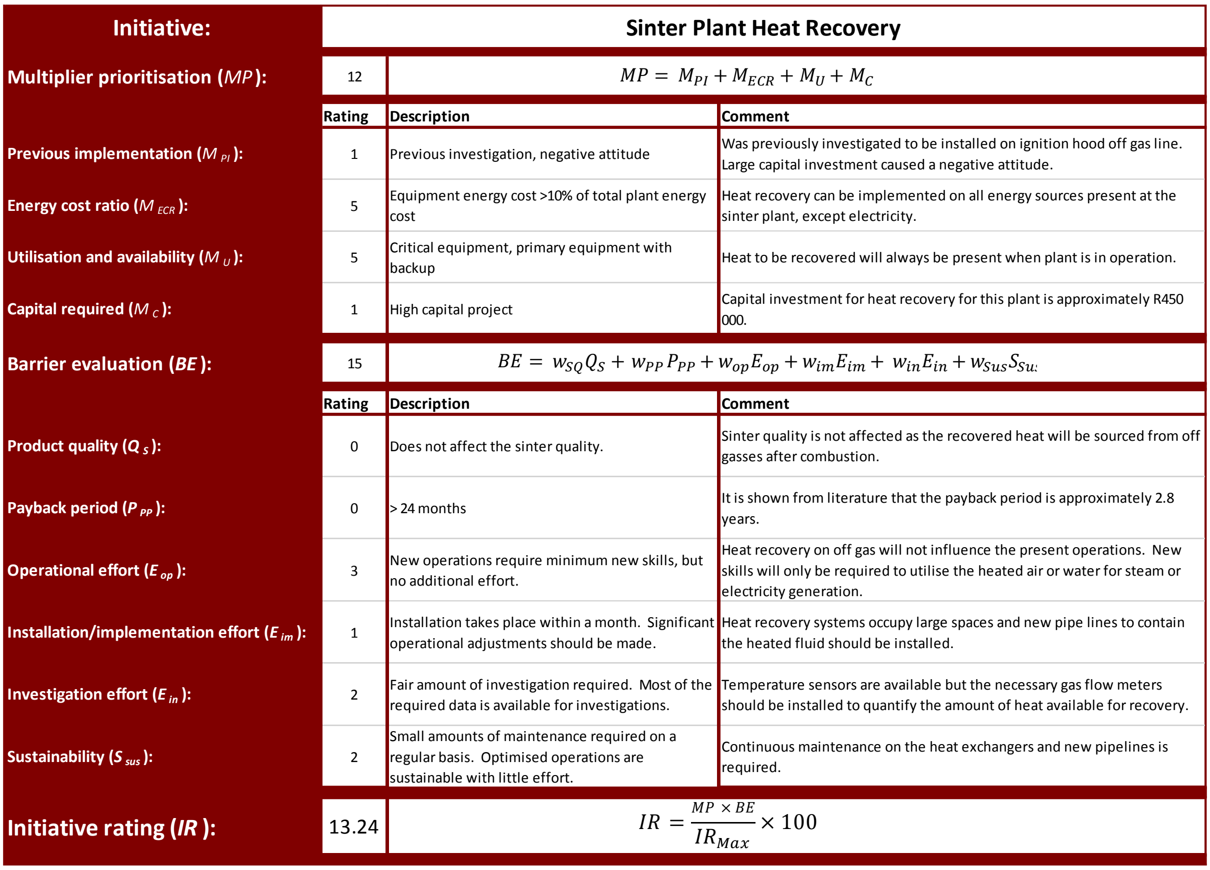
A *BE* value of 15 is obtained for the sinter plant heat recovery initiative after substituting the barrier rating values (Table 12) and barrier weights (Table 13) into Equation 9

The next step was to calculate the *IR* according to previously defined, Equation 5 and Equation 6, in Section 3.3.2.

Equation 5
$$IR = \frac{MP \times BE}{IR_{Max}} \times 100$$

Equation 6
$$IR_{Max} = MP_{Max} \times BE_{Max}$$

The *MP* and *BE* values were calculated in the previous steps and the MP_{Max} and BE_{Max} values are 20 and 68, respectively (Section 3.3). By substituting all the values into Equation 5 and Equation 6, the *IR* value for the sinter plant heat recovery initiative is 13.24%. The completed evaluation sheet for the sinter plant heat recovery initiative is displayed in Figure 26.



Initiative:	**Sinter Plant Heat Recovery**		
Multiplier prioritisation (*MP*):	12	$MP = M_{PI} + M_{ECR} + M_U + M_C$	
	Rating	**Description**	**Comment**
Previous implementation (M_{PI}):	1	Previous investigation, negative attitude	Was previously investigated to be installed on ignition hood off gas line. Large capital investment caused a negative attitude.
Energy cost ratio (M_{ECR}):	5	Equipment energy cost >10% of total plant energy cost	Heat recovery can be implemented on all energy sources present at the sinter plant, except electricity.
Utilisation and availability (M_U):	5	Critical equipment, primary equipment with backup	Heat to be recovered will always be present when plant is in operation.
Capital required (M_C):	1	High capital project	Capital investment for heat recovery for this plant is approximately R450 000.
Barrier evaluation (*BE*):	15	$BE = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Su}$	
	Rating	**Description**	**Comment**
Product quality (Q_S):	0	Does not affect the sinter quality.	Sinter quality is not affected as the recovered heat will be sourced from off gasses after combustion.
Payback period (P_{PP}):	0	> 24 months	It is shown from literature that the payback period is approximately 2.8 years.
Operational effort (E_{op}):	3	New operations require minimum new skills, but no additional effort.	Heat recovery on off gas will not influence the present operations. New skills will only be required to utilise the heated air or water for steam or electricity generation.
Installation/implementation effort (E_{im}):	1	Installation takes place within a month. Significant operational adjustments should be made.	Heat recovery systems occupy large spaces and new pipe lines to contain the heated fluid should be installed.
Investigation effort (E_{in}):	2	Fair amount of investigation required. Most of the required data is available for investigations.	Temperature sensors are available but the necessary gas flow meters should be installed to quantify the amount of heat available for recovery.
Sustainability (S_{sus}):	2	Small amounts of maintenance required on a regular basis. Optimised operations are sustainable with little effort.	Continuous maintenance on the heat exchangers and new pipelines is required.
Initiative rating (*IR*):	13.24	$IR = \frac{MP \times BE}{IR_{Max}} \times 100$	

Figure 26: Evaluation sheet for sinter plant heat recovery initiative

4.3.3 Oxygen and fuel enrichment

Sinter plant A requires combustion air at the ignition hood where *COG* is burned to heat the sinter mixture. Nitrogen in the combustion air dilutes the reactive oxygen contained in the combustion air mixture and absorbs a large portion of the heat that is otherwise required for the combustion process. Combustion can be improved by enriching the combustion air supply to the ignition hood with oxygen.

The feasibility of installing oxygen injectors in the combustion air supply line to the ignition hood must be investigated. Safety regulations limit the enrichment to approximately 5% and the actual cost of the oxygen must be considered.

The completed evaluation sheet with the ratings and comments for the oxygen and fuel enrichment initiative is provided in Appendix A.

4.3.4 Segregated material charging

Sinter plant A was built more than 30 years ago and significant technology improvements have since been made as far as sinter charging equipment is concerned. It would therefore be sensible to upgrade the current charging chute for improved material charging. The nett impact of this initiative would be a higher sinter quality as particles can be more specifically arranged during the sinter bed charging process.

The feasibility of replacing the existing material charging chute with the latest segregated slit wire material charging chute was investigated. The completed evaluation sheet and outcome is provided in Appendix A.

4.3.5 Production scheduling

Valuable information was gathered on the production specifications of Sinter plant A during the plant investigation. The information indicated that the sinter production capacity of Sinter plant A is greater than the sinter consumption rate of the *BF*.

The 4.5 MW and 3.3 MW fans used in the production process consume large amounts of electricity. Varying electricity tariffs between peak and off-peak TOU periods allow the possibility for significant cost savings. Sinter production could be increased during off-peak, lower tariff TOU periods and decreased during high tariff peak TOU periods. The stock piles at Sinter plant A will serve as a buffer to ensure a constant flow of sinter to the *BF*.

The completed evaluation sheet of this initiative can be found in Appendix A.

4.3.6 Automated sinter control

The initiative is to automate the *COG* flow to the ignition hood by installing an automated control system. This automated system will regulate the gas flow rate into the ignition hood by monitoring the temperature and increase the gas flow rate if the temperature drops below a predefined temperature set point.

According to literature studies the Arduino is an affordable and seemingly reliable control system. Temperature inside the ignition hood is measured by means of a thermocouple and the gas flow is regulated with a proportional–integral–derivative (PID) controller.

The completed evaluation sheet for the automated sinter control is provided in Appendix A.

4.3.7 Sinter bed optimisation

Several studies from literature indicated that the sinter production rate can be improved by increasing the depth of the sinter bed. The existing sinter strand and sinter charging equipment will have to be adjusted for achieving the maximum sinter bed depth.

This initiative may require improved sintering equipment such as a new charging chute to accommodate a deeper sinter bed and derive maximum benefit.

The completed evaluation sheet with the ratings and comments for this initiative is provided in Appendix A.

4.3.8 Air leakage reduction

Figure 24 indicate the location of the large induced draft fans. During operation, these fans extract air through the sinter bed to improve coke combustion and the sintering process. False air is drawn into the fan ducting reducing the volume of air passing through the sinter bed. This reduces the efficiency of the sintering process.

Large amounts of false air are drawn into the fan ducting at Sinter plant A. The initiative is to seal the fan ducting and reduce the amount of false air in the process. The scope of the initiative can be widened to introduce air leakage repairs during maintenance windows.

The completed evaluation sheet with the ratings and comments for the air leakage reduction initiative can be seen in Appendix A.

4.3.9 Sinter quality optimisation

The quality of the sinter produced by Sinter plant A can be improved by implementing several initiatives identified in literature. Enhanced sinter quality would improve both sinter productivity and *BF* efficiency. As the *BF* consumes large amounts of sinter, a small improvement in sinter quality could result in significant energy savings at the *BF* [24].

The following initiatives are investigated to improve the sinter quality of Sinter plant A:

- Substituting the coke breeze and anthracite in different ratios;
- Changing the carbon content in the sinter mixture;
- Determine the optimal fuel mixture;
- Alter particle sizes of raw material to improve air flow through the sinter bed;
- Optimise additive ratios, such as the dolomite, olivine or serpentine and limestone to promote the slag formation in the *BF*; and
- Experiment with different iron ore fines.

The completed evaluation sheet with the ratings and comments for the sinter quality optimisation can be found in Appendix A.

4.3.10 Summary of initiative ratings

The cost saving evaluation sheets and functions were completed and the final initiative ratings are displayed in Figure 27. These results can now be utilised to conduct a detailed investigation of the most feasible alternative(s).

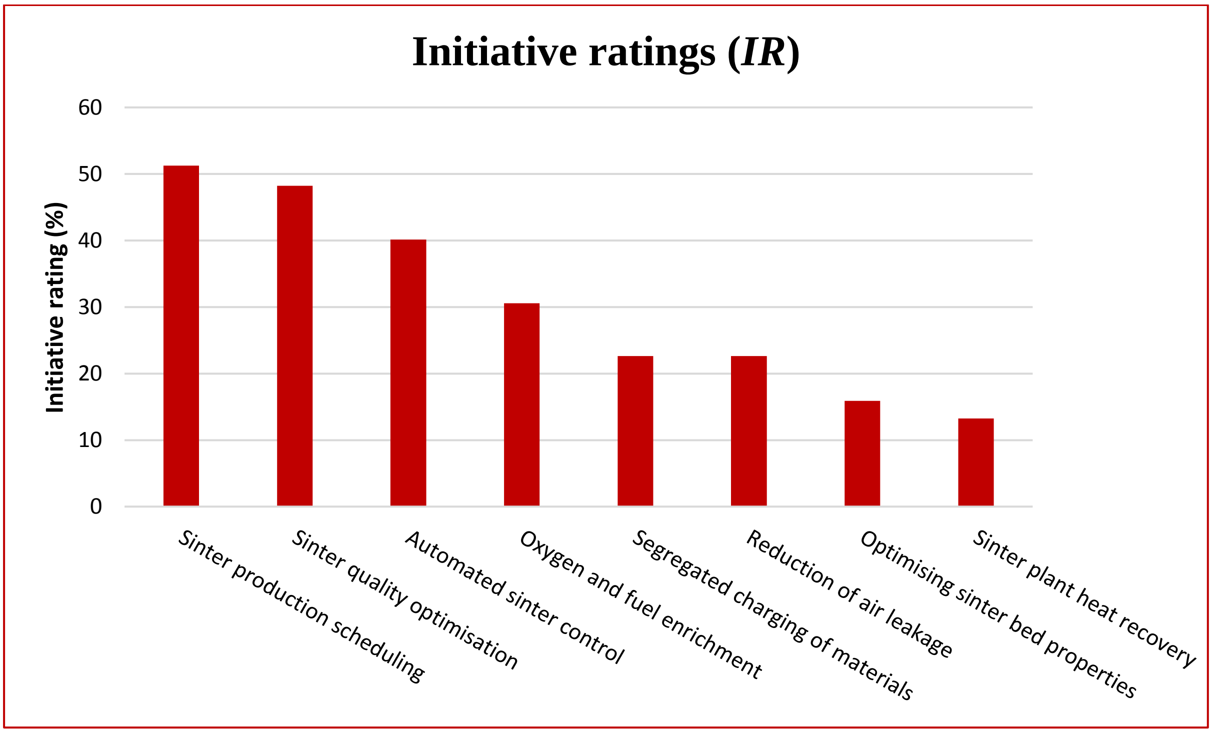


Figure 27: Initiative rating summary

4.4 Detailed investigation through simulation

4.4.1 Preface

The results of the cost saving initiative evaluation model in Section 4.3 indicate that sinter production scheduling was rated as the most feasible. The following step in the methodology is to conduct a detailed investigation of the identified initiative(s). A simulation will be developed using Microsoft Excel to assist with a more detailed investigation.

4.4.2 Data inventory and characterisation

Available data sheets from the data inventory were revisited. The plant is characterised with sinter production as the energy driver. Before any modification is made to production schedule, it must be proved that there is a direct correlation between the energy driver and electricity consumption.

Section 4.2.4 provides valuable data and metrics with regard to the three possible fan configurations at Sinter plant A. These fans are large consumers of electricity and the strong correlation between the sinter production and electrical consumption of the fans are evident from Figure 28. The correlation clearly indicates that electricity cost savings can be maximised with optimal production scheduling.

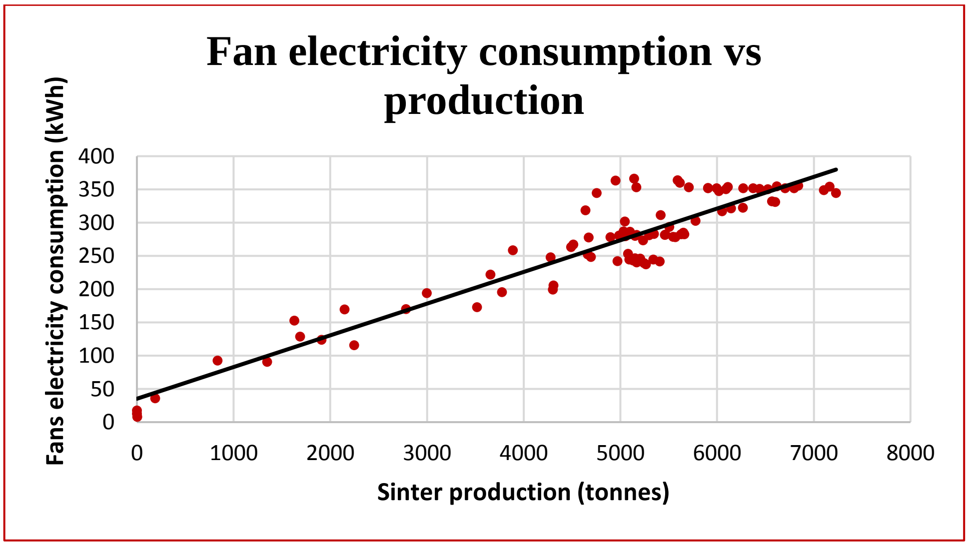


Figure 28: Relation between energy driver and energy consumption

The next step in the characterisation process is to perform a static analysis for evaluating the improvement potential for the production schedule. This is achieved by comparing current production with maximum production capacity.

The following equations from Section 3.4.2 are used:

Equation 12 $$Production\ capacity = R_{eff} \times E_{Av} \times Calender\ hours$$

Equation 13 $$R_{eff} = R_{emp} \times E_{Re}$$

Equation 14 $$E_{Re} = 1 - \frac{Unplanned\ stoppage\ hours}{calendar\ hours}$$

Equation 15 $$E_{Av} = 1 - \frac{Planned\ maintenance\ hours}{calendar\ hours}$$

where R_{eff} represents effective production rate;
E_{Av} represents equipment availability;
R_{emp} represents empirical production rate; and
E_{Re} represents equipment reliability.

According to Table 10, the maximum empirical production rate with all fans running is 280 t/h. Planned maintenance and the duration of unplanned breakdowns can be obtained from the electricity consumption profiles as provided in (Figure 29 to Figure 31) and operational logs.

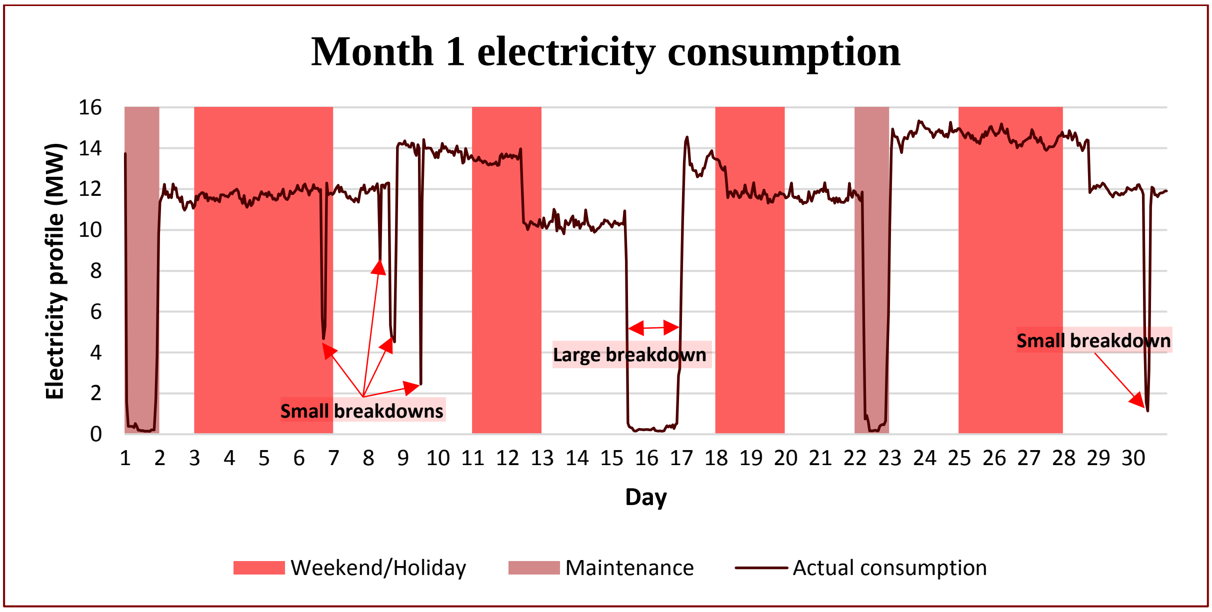


Figure 29: Month 1 electricity consumption profile

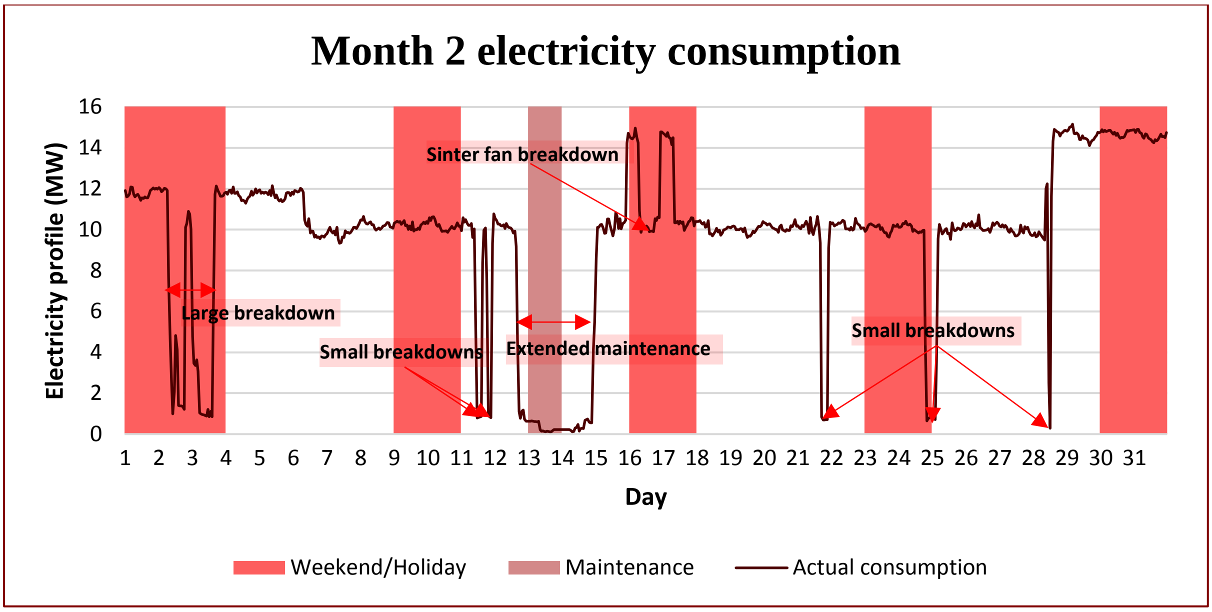


Figure 30: Month 2 electricity consumption profile

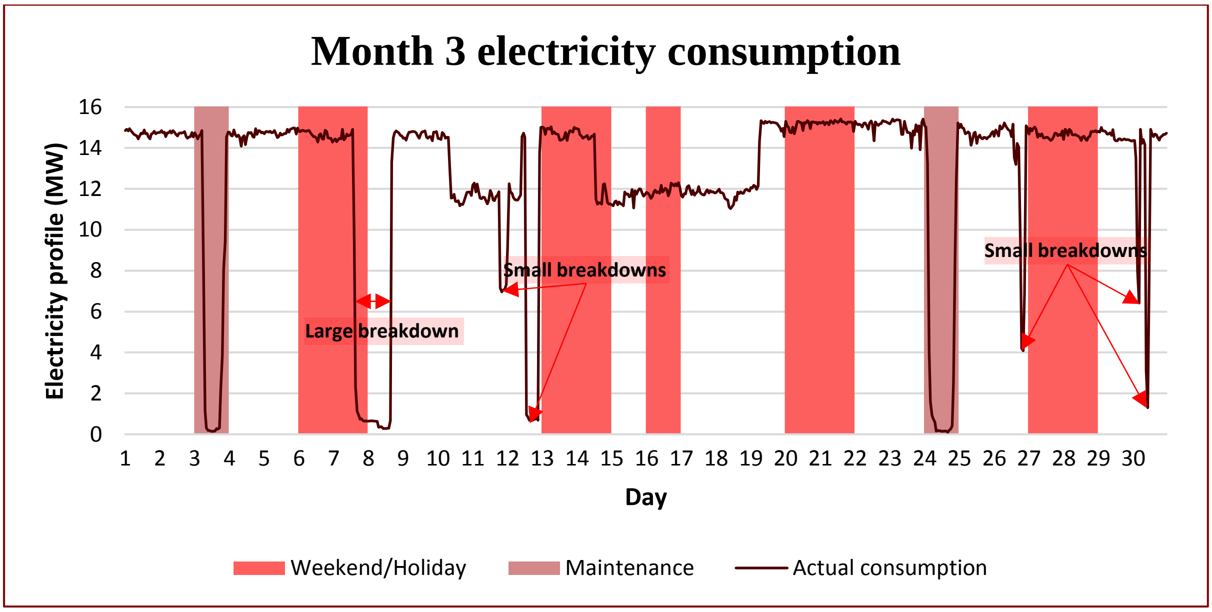


Figure 31: Month 3 electricity consumption profile

The maximum production capacity (Equation 12) for each month can only be determined once each of the required variables have been calculated. The production scheduling margin can be expressed as the spare production capacity. The larger the spare production margin the higher the opportunity for improving the production schedule. The production scheduling margin is provided in Figure 32.

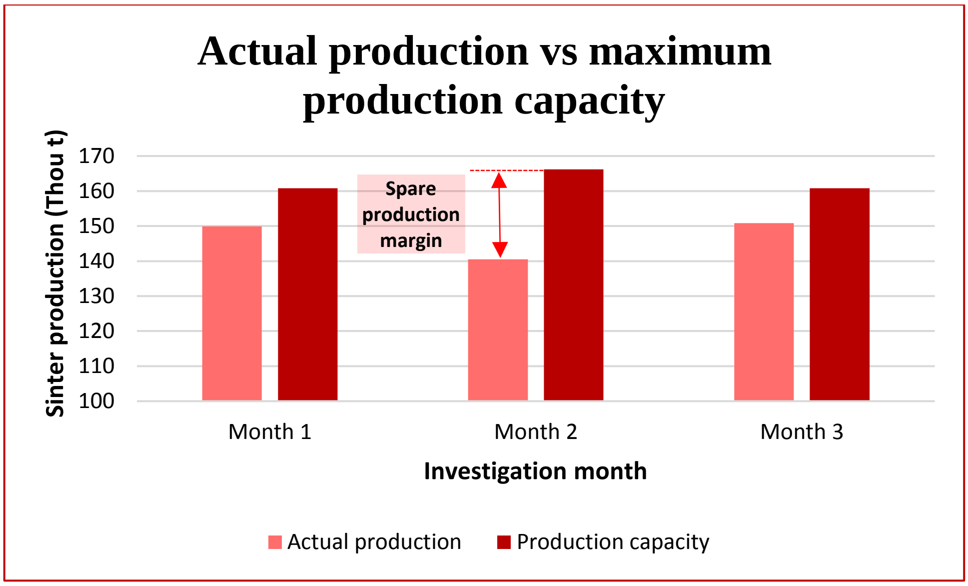


Figure 32: Production scheduling margin

During the high-level investigation, plant personnel indicated and confirmed that the plant can operate on three different fan configurations as described in Table 10. These fan configurations can be characterised for the amount of power consumed at Sinter plant A. The frequency of each specific power consumption reading over the 3-month baseline period is provided in Figure 33. This indicates the present set points for the various fan configurations.

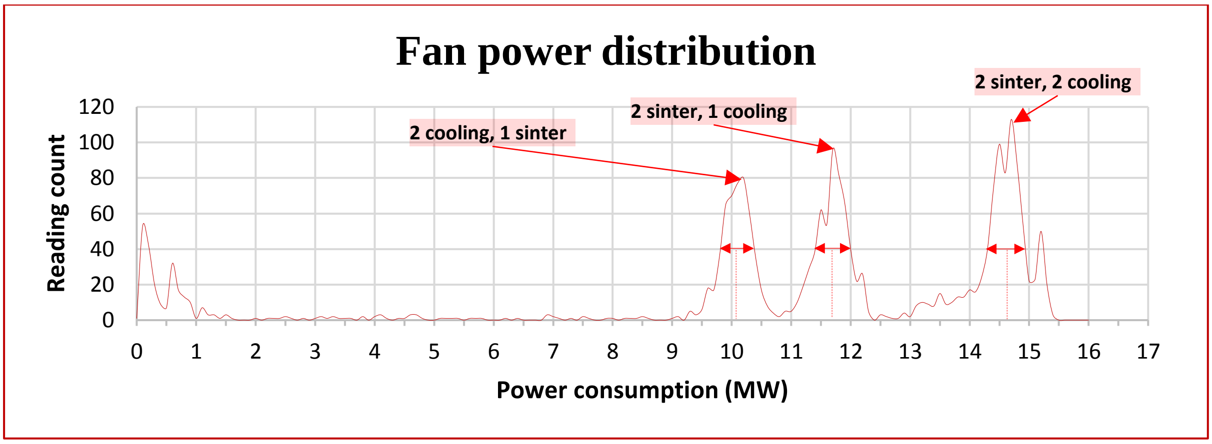


Figure 33: Fan configuration frequencies

Table 14 provides a summary of the average power consumptions as obtained from Figure 33. These values will be utilised as the power consumption inputs for the simulation.

Table 14: Summary of fan configuration power consumptions

Fan configuration	**Power consumption (kW)**
4 Fans, 2 sinter and 2 cooling	14 600

2 Sinter fans and 1 cooling fan	11 700
1 Sinter fan and 2 cooling fans	10 100

Production can now be characterised for each fan configuration. By applying Equation 12 to Equation 15 the effective production rates for each fan configuration can be calculated by utilising the empirical production rates as provided in Table 10. The effective production rates in Table 15 will be utilised as the production inputs for the simulation.

Table 15: Summary of effective production rates for different fan configurations

Fan configuration	Reported prod rate (t/h)	Effective prod rate (t/h)
4 Fans, 2 sinter and 2 cooling	280	250
2 Sinter fans and 1 cooling fan	240	210
1 Sinter fan and 2 cooling fans	200	190

4.4.3 Baseline selection

Section 3.4.3 indicated a baseline period of at least three months should be utilised and that the data should represent normal operational days as far as possible. The last three months were chosen as the baseline period. This period is a true representation of normal operations as it includes both summer and winter operations. Abnormal days were excluded from the baseline during calculations.

Figure 34 to Figure 36 provide the simulated and actual electricity consumption profiles for the baseline. Through visual inspection there is no evidence of attempts to reduce electricity consumption during peak periods.

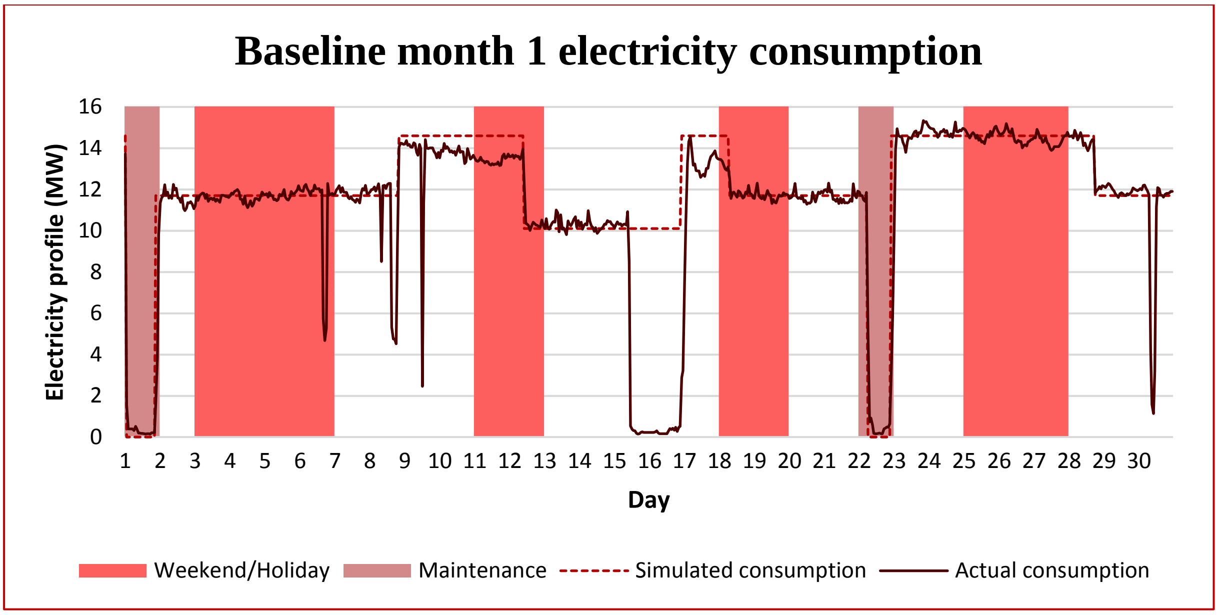


Figure 34: Electricity consumption for Baseline month 1

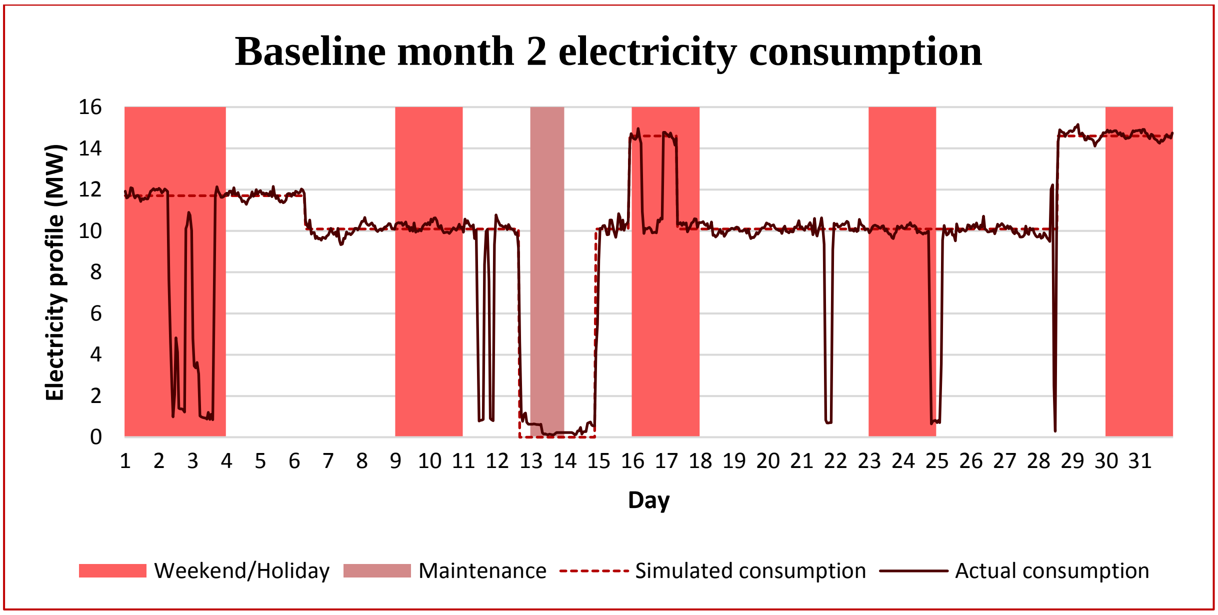


Figure 35: Electricity consumption for Baseline month 2

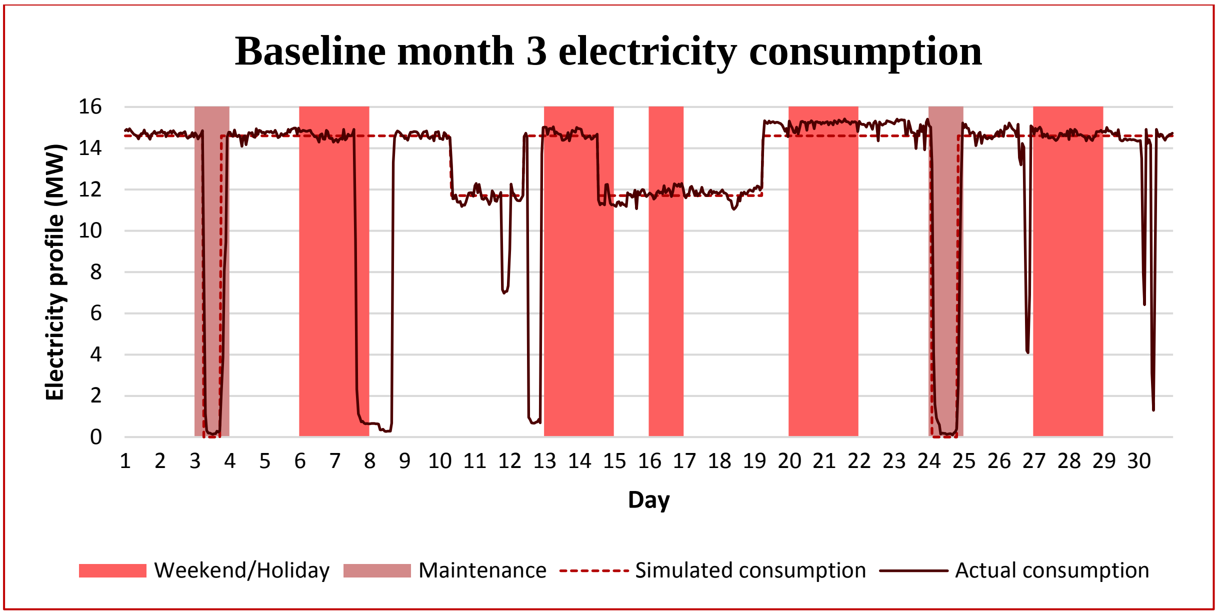


Figure 36: Electricity consumption for Baseline month 3

Figure 37 indicates the average weekday profile baseline for Sinter plant A. This profile represents an average of all normal operation days across the baseline period. The average weekday profile baseline indicates that the electricity consumption remains constant throughout the day. None of the monthly or daily electricity consumption profiles indicate any actions or attempts to perform a load shift.

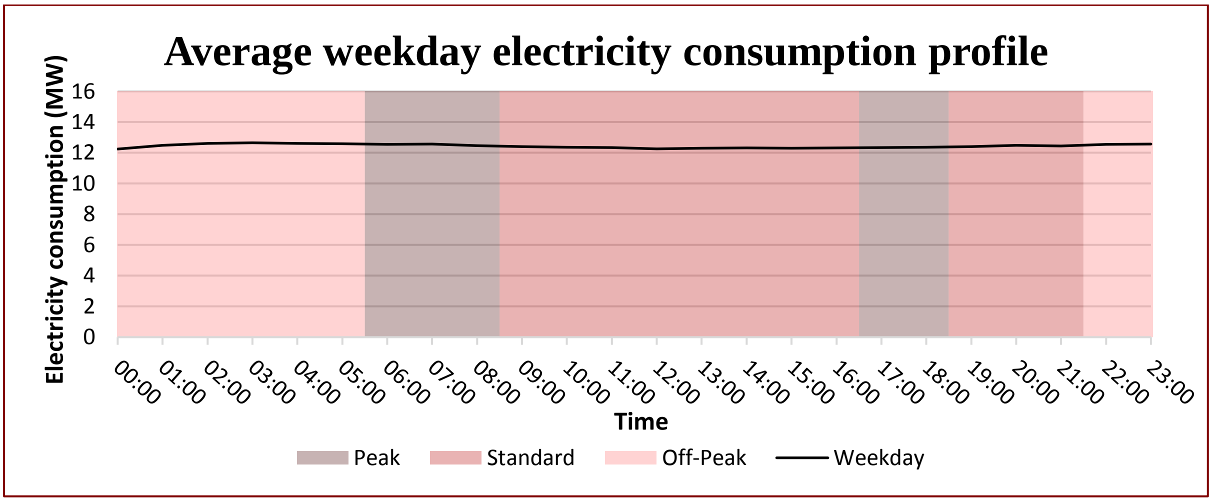


Figure 37: Average weekday electricity consumption profile

Section 4.4.2 identified a direct relation between the fan schedule and sinter production. Any change to the daily production would have a direct impact on electricity consumption. As a result, it is now possible to scale the electricity profile baselines to be energy neutral across the entire baseline period.

The baseline is scaled by using the value as calculated by Equation 17. The potential cost saving can now be determined by comparing the energy neutral baseline with the actual electricity consumption during the evaluation period.

Equation 17 $$B(E) = E \times \frac{Total\ electricity\ consumption}{Baseline\ electricity\ consumption}$$

where *B* represents the function of the scaled baseline;
E is the actual instantaneous electricity consumption for the specific hour;
Total electricity consumption is the accumulated electricity consumption for the entire day;
Baseline electricity consumption is the total accumulated electricity consumption according to the baseline in Figure 37.

4.4.4 Simulation and verification

The source data indicates frequent exchanges of sinter between different plants within the group to maintain sinter stock levels. The financial and production departments within the group utilise Equation 18 to determine the required stock levels for each processing day.

Equation 18: Sinter stock level calculation

$$SL = SL_p + P_d - C_d + Imp - Exp$$

where SL represents the stock level;
SL_p represents the closing stock for the previous day;
P_d represents the daily production;
C_d represents the daily consumption;
Imp represents the imports; and
Exp represents the exports.

A reconciliation of sinter exchanges for the past year indicated that the total imports and exports between plants balance to within 10% per month. Equation 18 can therefore be simplified to only consider sinter production and *BF* consumption.

Any simulation must be verified before use to ensure accuracy and establish reliability of the results. Figure 38 indicates the comparison between the actual and simulated sinter stock levels over the 3-month baseline period.

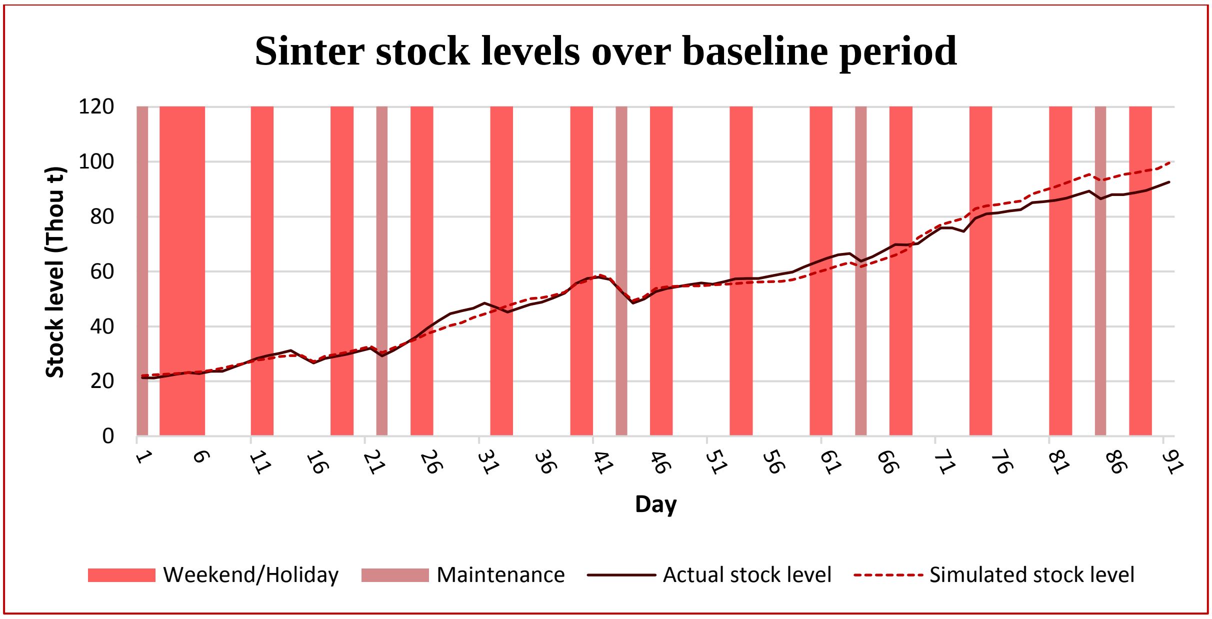


Figure 38: Planned sinter stock levels over baseline period

This close relation between the simulated and actual stock levels in Figure 38 proves the accuracy of the simulation. The low stock level error between the two graphs as provided in Figure 39 imply a high reliability of above 90%. As a result, the simulation can be considered to be verified and can therefore be utilised for further simulations.

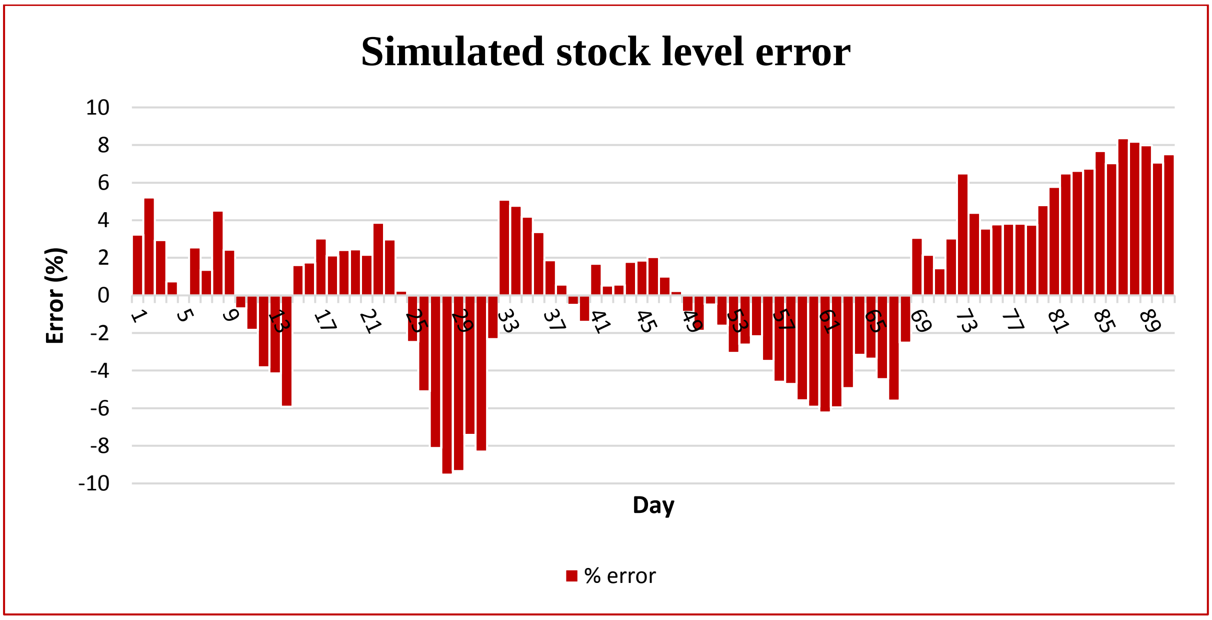


Figure 39: Simulation error percentage

The intended monthly production targets can be derived from the baseline consumption profiles provided in Figure 34 to Figure 36. These monthly production targets were utilised as input into the simulation to determine the optimal production schedule for rendering the same production at a reduced electricity cost.

The Eskom TOU tariffs are provided in Figure 40 and encourages maximum production to be scheduled during off-peak and standard periods. The 3-weekly, 8-hour maintenance slots must be scheduled to take place from 06h00 to 14h00 on the particular days. The simulation attempted to avoid all production during evening peak periods.

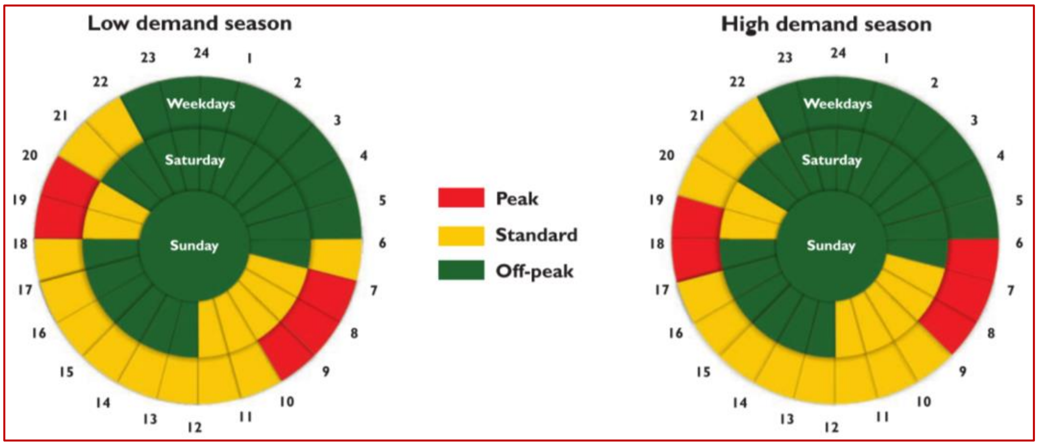


Figure 40: Eskom TOU periods[10]

The significant cost difference for 2017/2018 between peak and off-peak tariffs can be noted from Table 16.

Table 16: Electricity tariffs for different TOU periods[11]

Active energy charge (R/kWh)	Low demand season [Sep-May]			High demand season [Jun-Aug]		
	Peak	Standard	Off-Peak	Peak	Standard	Off-Peak
	0.8158	0.5613	0.3562	2.5003	0.7574	0.4114

The final parameters to be incorporated into the simulation are the sinter stock levels. Section 4.2.4 specified that stock levels range between 15 000 and 32 000 tonnes. Ranking the fan configurations according to the highest production rates will allow the simulation to schedule maximum production into off-peak periods. The fan configurations are therefore ranked according to the following hierarchy:

1. 4 Fans, 2 sinter and 2 cooling

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[10] Eskom time-of-use tariff period wheels obtained from Eskom, Tariffs and Charges 2017/2018 booklet. [Date accessed: 2017-07-07]

[11] Eskom time-of-use obtained from Eskom, Tariffs and Charges 2017/2018 booklet. [Date accessed: 2017-07-07]

2. 1 Sinter fan and 2 cooling fans
3. 2 Sinter fans and 1 cooling fan

Stock levels will be calculated by combining Equation 18 and the effective hourly production and consumption rates. Derived Equation 19 will be utilised in the simulation to calculate and maintain stock levels within specified boundaries.

Equation 19: Derived sinter stock level calculation

$$SL_i = SL_{i-1} + R_{EP} \times t - R_{EC} \times t$$

where SL_i represents the present stock level (t);
SL_{i-1} represents the previous stock level (t);
R_{EP} represents the effective production rate (t/h);
R_{EC} represents the effective consumption rate (t/h); and
t represents the interval duration (h).

The literature refers to the process of shifting the core production load from one processing period to the next as load shifting. It was noticed in Section 4.4.3 that no evidence exists of prior attempts to reduce electricity consumption during peak periods through load shifting. The simulation was utilised to determine the maximum optimisation that would have been possible during the last 3-month period. Several load shift opportunities were identified for the specific baseline period and the possible savings over the period were identified.

Figure 41 shows sixteen days that were identified by the simulation where the electricity consumption could have been reduced during the evening peak periods. It also indicates that additional savings would have been possible by switching to 3-fans.

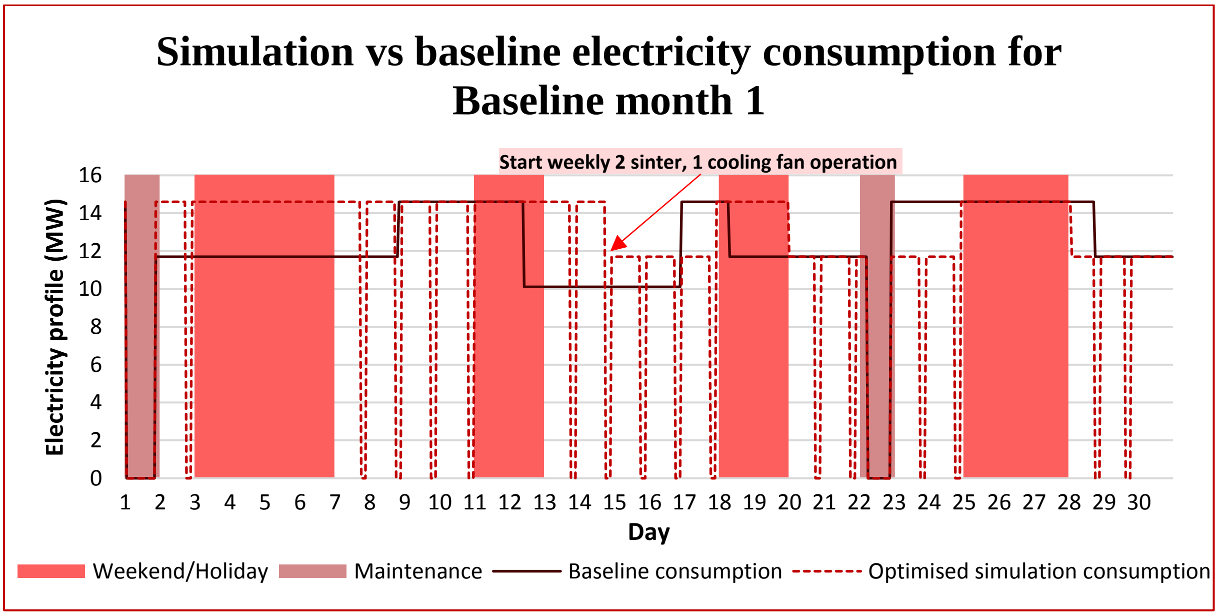

Figure 41: Electricity consumption simulation profile for Baseline month 1

Figure 42 indicates seventeen days where the electricity consumption could have been reduced during the evening peak period. The low production target for baseline month 2 allowed a daily load shift during the evening peaks. Production could be reduced to the lowest production rate from Day 12 and an extended maintenance shut down could be accommodated on Day 14.

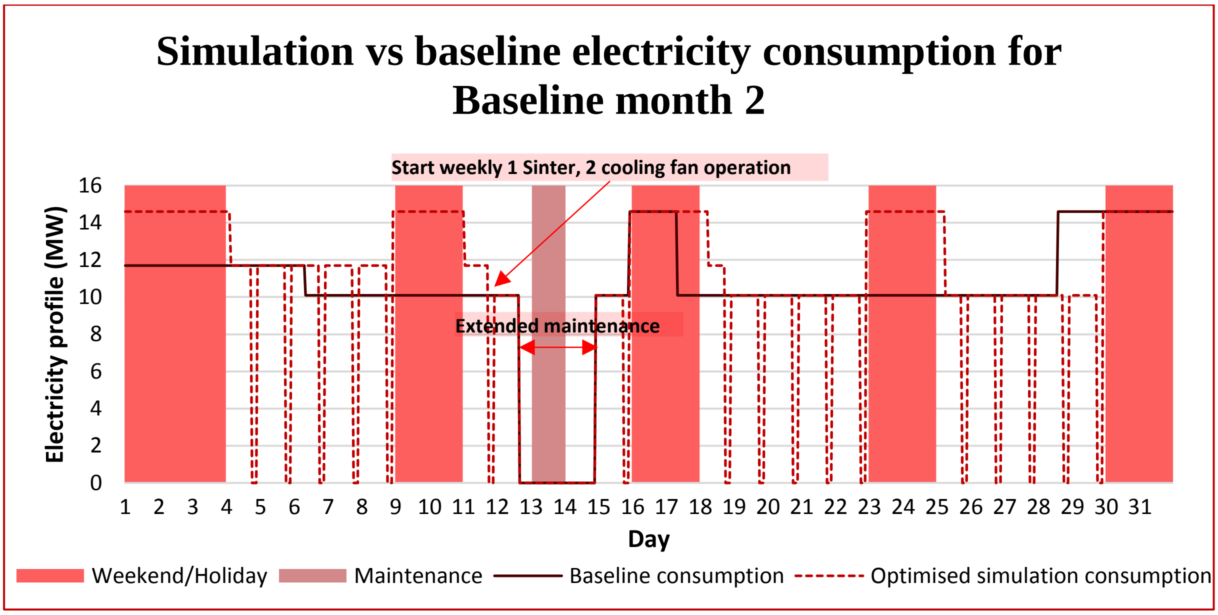

Figure 42: Electricity consumption simulation profile for Baseline month 2

In Figure 43, high production targets restricted the simulation and only identified five days on which load shifts would have been possible.

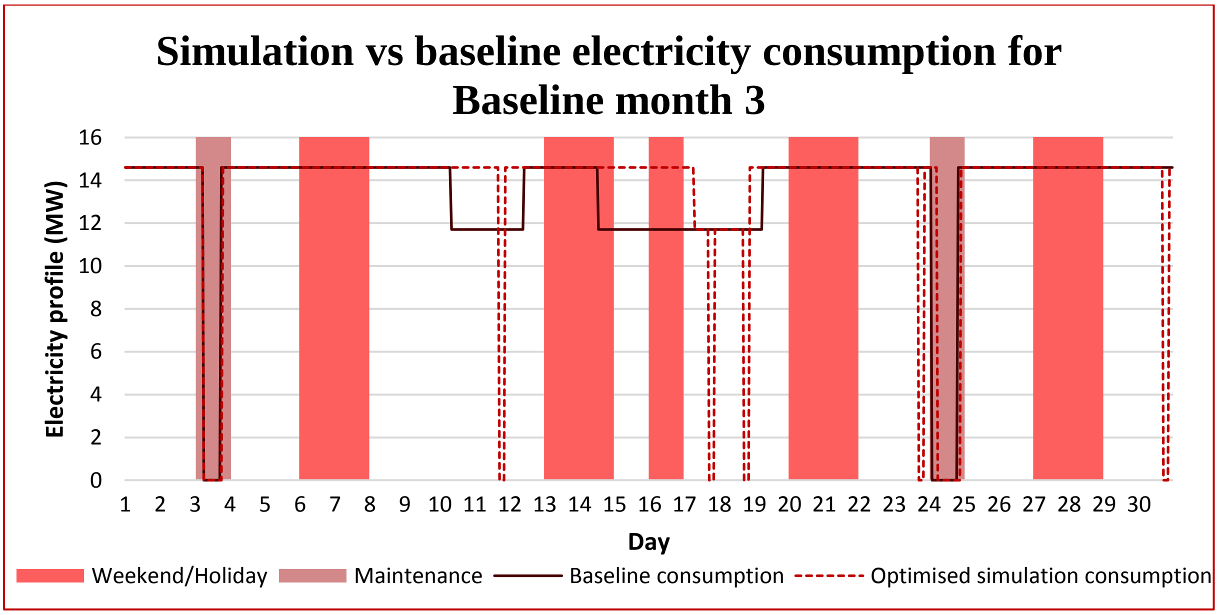

Figure 43: Electricity consumption simulation profile for Baseline month 3

As for any typical processing plant, production is the most important objective of Sinter plant A. It is therefore critical that the sinter stock levels remain within the specified range. In Figure 44 the simulated stock level is compared with the actual stock level as recorded during the 3-month baseline period.

Two instances were identified where the simulated sinter levels dropped below the actual stock levels throughout the baseline period. The maximum difference in sinter levels during these instances proved to be insignificant as it is less than 5% and the deficit was recovered within 1 week.

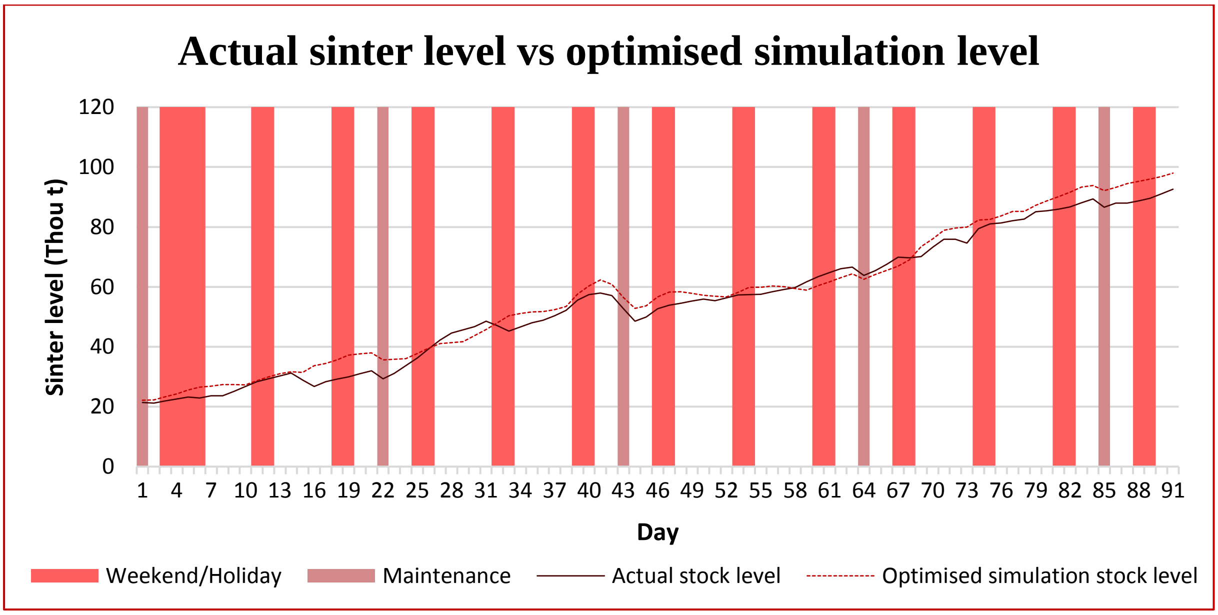

Figure 44: Comparison of sinter levels

Further analysis of the simulation results indicated that production was spread across each month with maximum production over weekends. The pie charts contained in Figure 45 and Figure 46 provide a better visualisation of the electricity consumption for each tariff period and indicates how the electricity load could have been shifted away from peak periods.

Comparison of Figure 45 and Figure 46 indicates that the electricity consumption during the peak periods could be reduced by 3%, that of standard periods by 2% whilst the off-peak consumption increases by 5%.

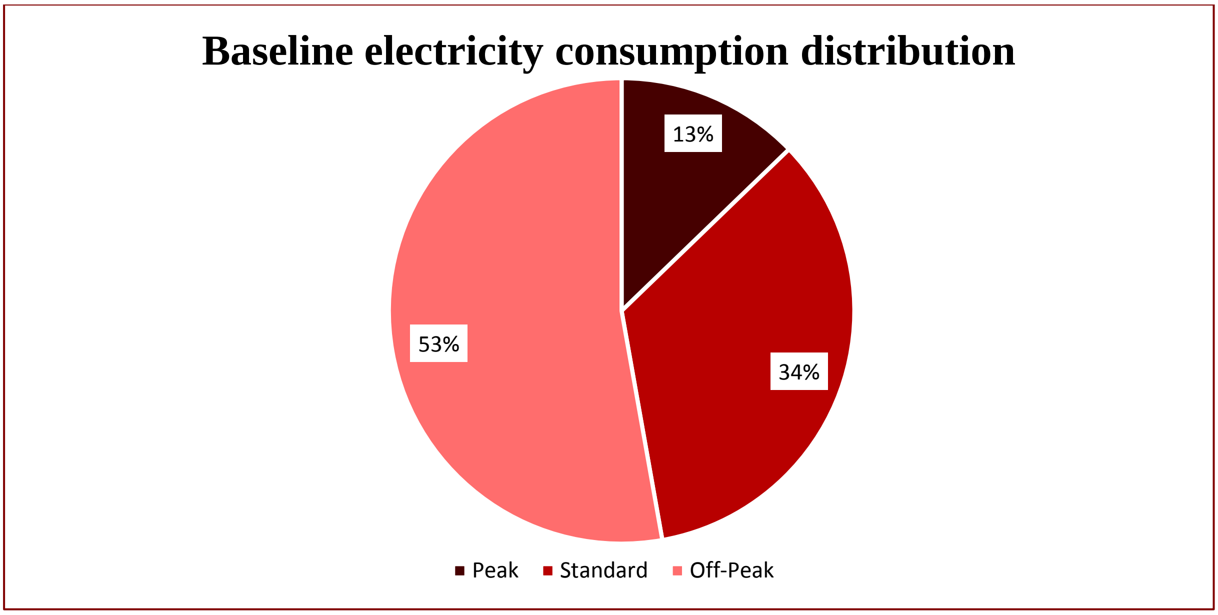

Figure 45: Electricity consumption distribution during 3-month baseline period

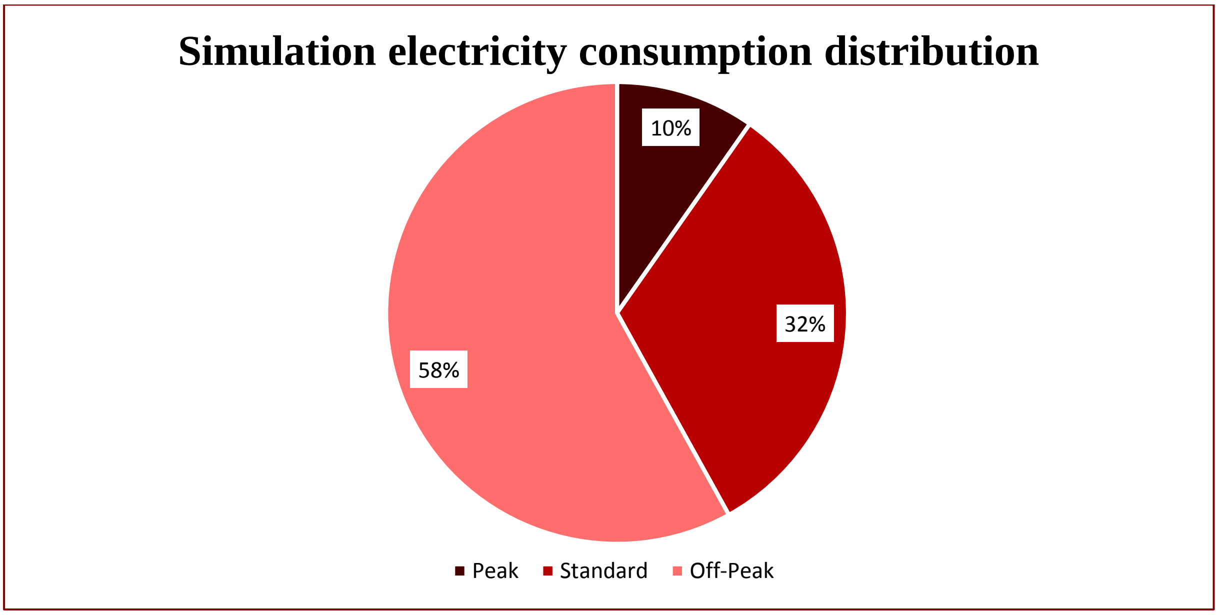

Figure 46: Electricity consumption distribution according to the optimised simulation

Although these changes seem to be insignificant, it has a significant impact on the cost distribution. A comparison of Figure 47 and Figure 48 indicates reductions of R1.4 million and R400 000 during peak and standard periods, respectively. At the same time, off-peak costs increase by R500 000.

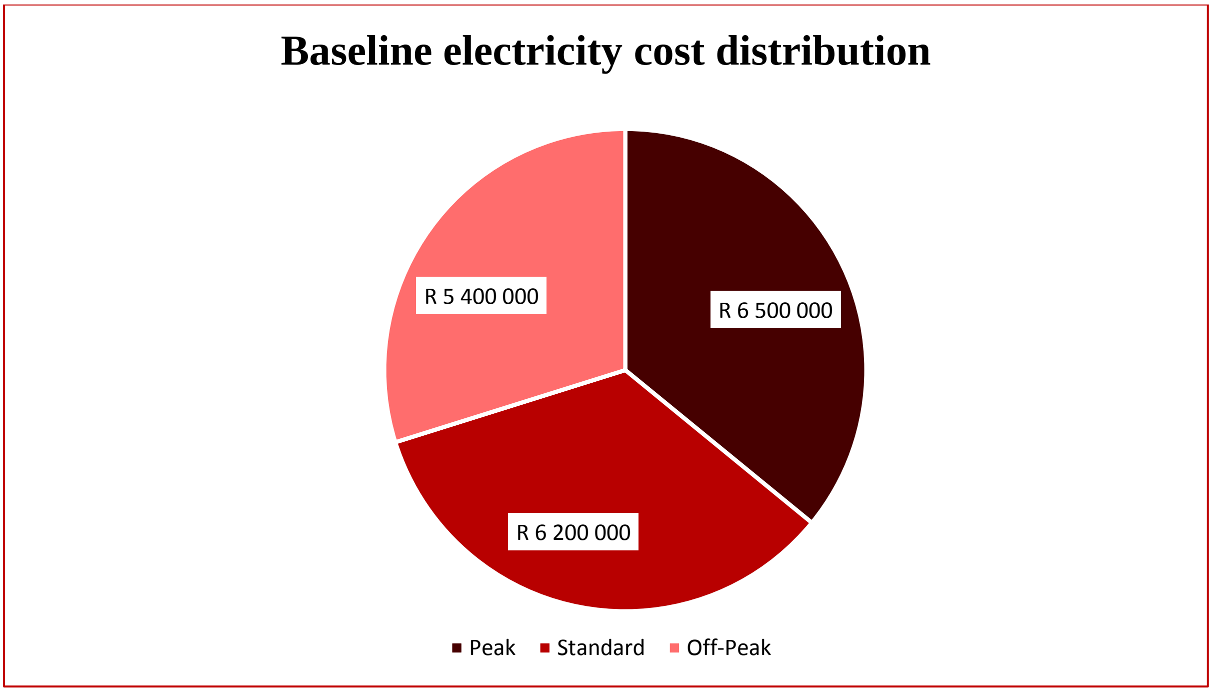

Figure 47: Electricity cost distribution during baseline period

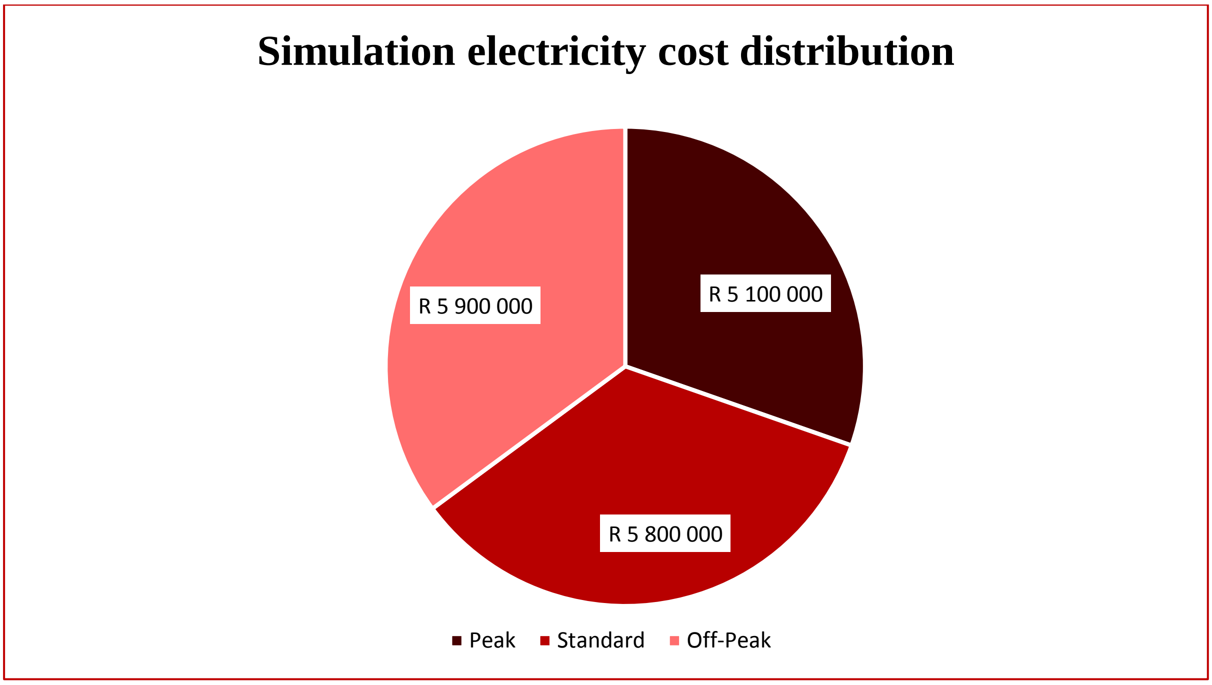

Figure 48: Electricity cost distribution according to the simulation

The nett saving of R1.3 million is indicated in Figure 49. The effect of the tariff change from low to high demand season between months 1 and 2 are indicated in Figure 49. The savings increased by more than 3 times for the second month implying the significance of implementing a load shift during high-demand season. As previously mentioned, the production targets during month 3 were high leaving limited opportunities for production rescheduling.

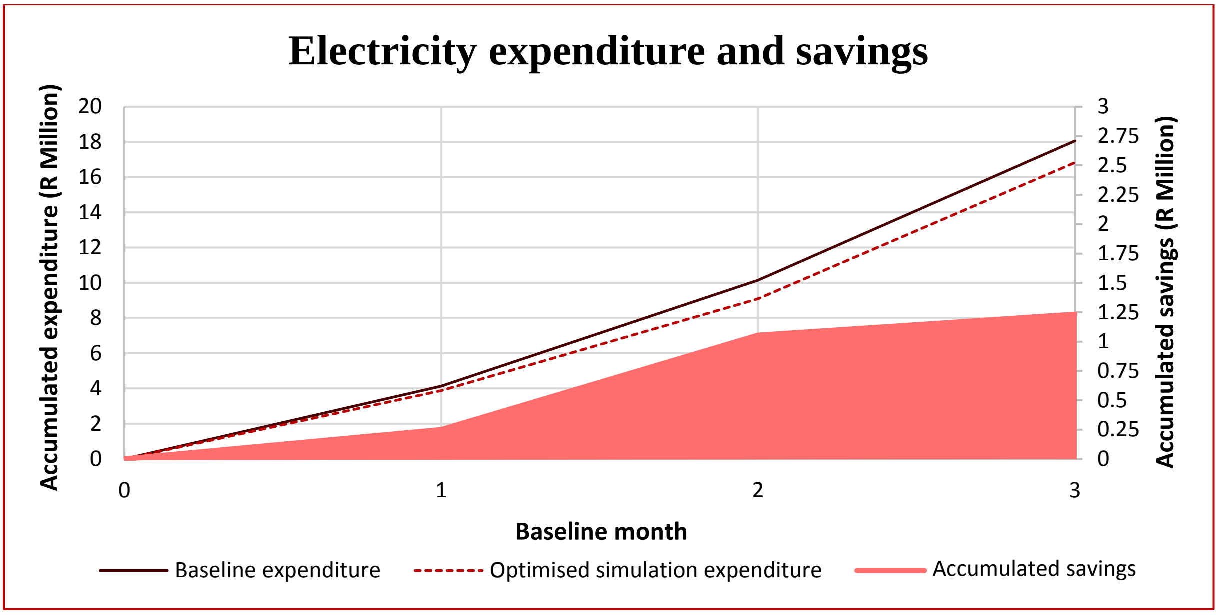

Figure 49: Electricity expenditure and savings according to the simulation

4.5 Validation of model on case study

4.5.1 Preface

The developed evaluation method can be validated if the identified cost saving initiative can be implemented to achieve actual cost savings. Analysis of the simulation results indicated the possibility for the optimisation of production. The results of the simulation and significant cost saving opportunities were presented to plant personnel at Sinter plant A.

4.5.2 Pilot study

The intention was to prove that partial or complete production shutdown was possible, over and above the normal 8-hour maintenance shut down, without affecting monthly production. Sinter plant management agreed to allow five days for conducting the pilot studies.

The results of the pilot studies would demonstrate the potential for re-scheduling production on Sinter plant A. The plant shut down was scheduled for 4-hours on each day of the pilot study starting from 18h00 thereby spanning the evening peak from 18h00 to 20h00 and two standard tariff hours from 20h00 to 22h00. A full production shutdown was done for each day of the pilot studies.

The power consumption profiles for the 5 pilot study days are provided in Figure 50 to Figure 54. Figure 50 indicates a load shift of approximately 14 MW. During the last four pilot study days, production was already running on 3-fan operations therefore a reduced load shift of 9 MW was achieved on each of the days. All production targets were met during the month of the pilot studies.

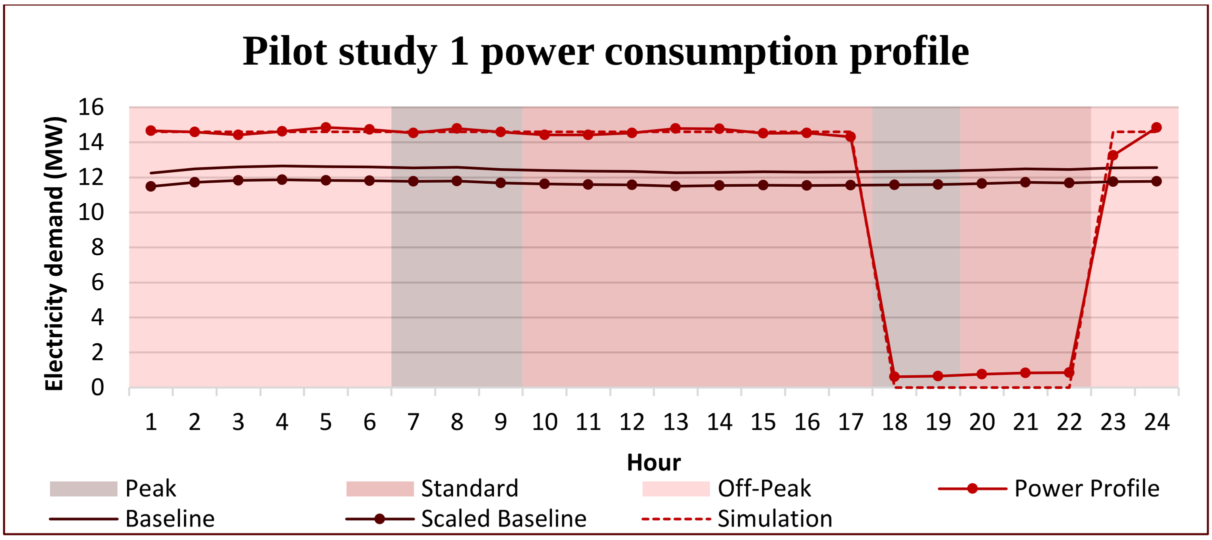

Figure 50: Power consumption profile for pilot study 1

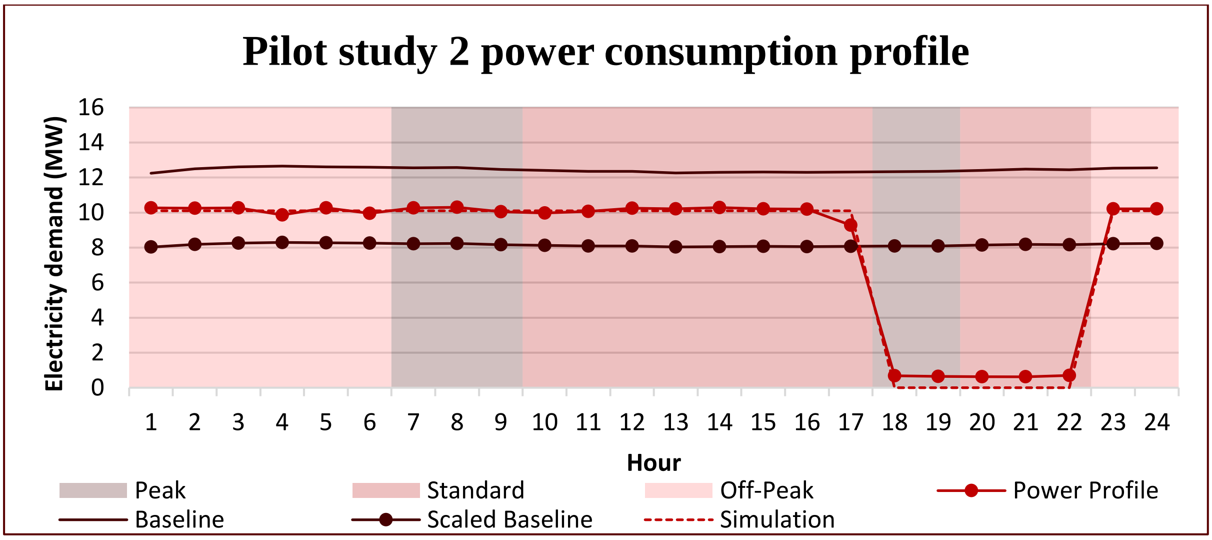

Figure 51: Power consumption profile for pilot study 2

A delay during maintenance on the previous day resulted in a delayed start-up. The delay during the first hour of the third pilot study day is visible in Figure 52.

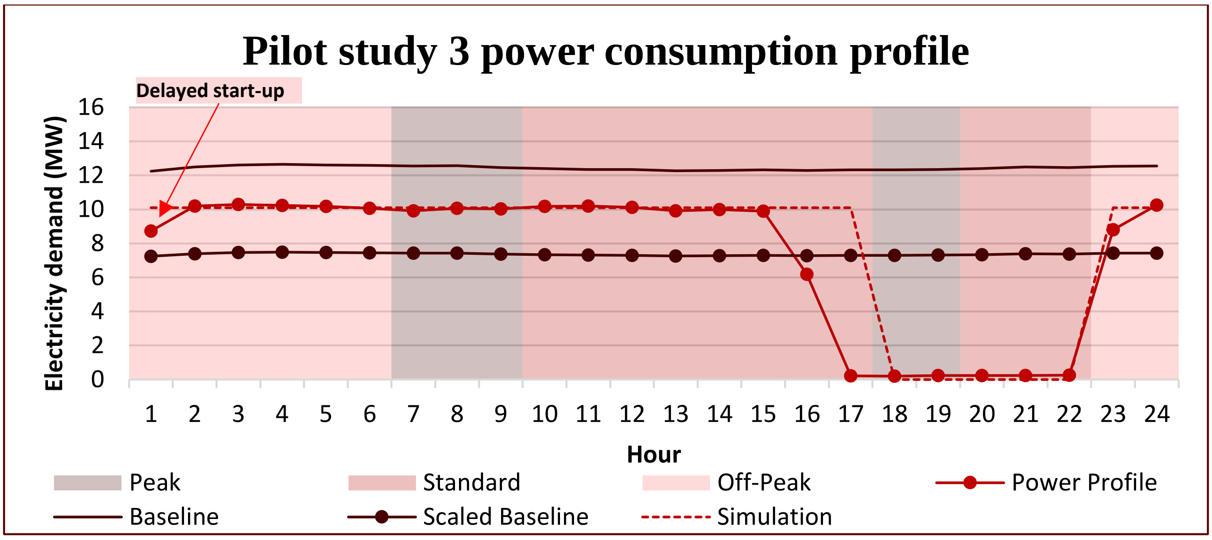

Figure 52: Power consumption profile for pilot study 3

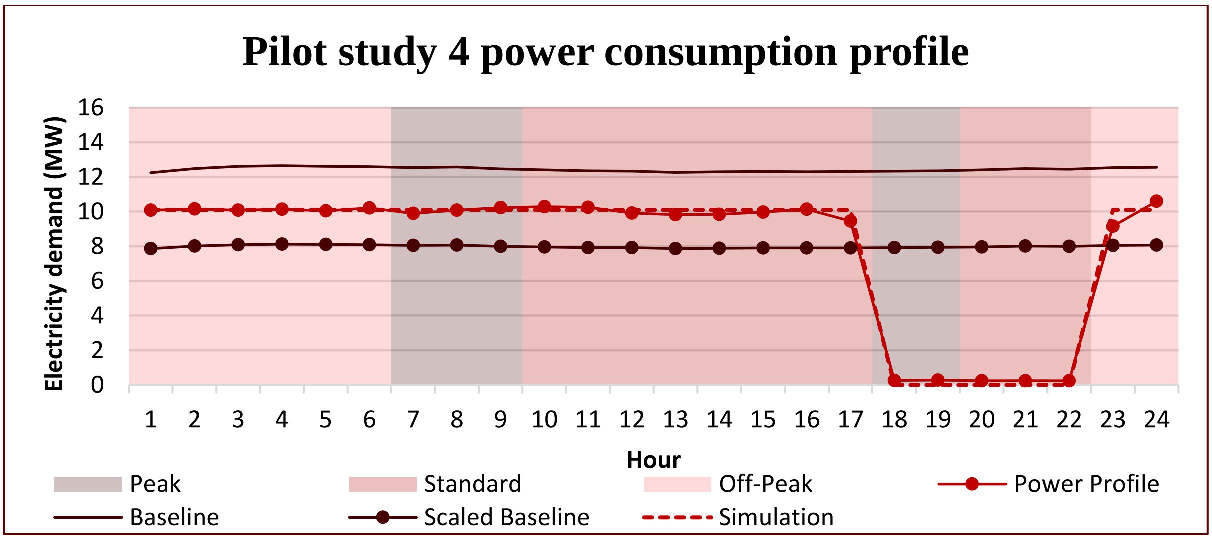

Figure 53: Power consumption profile for pilot study 4

Production was increased to 4-fan operation after the final pilot study. Figure 54 indicates the increase in electricity consumption during the last hours of the fifth pilot study day.

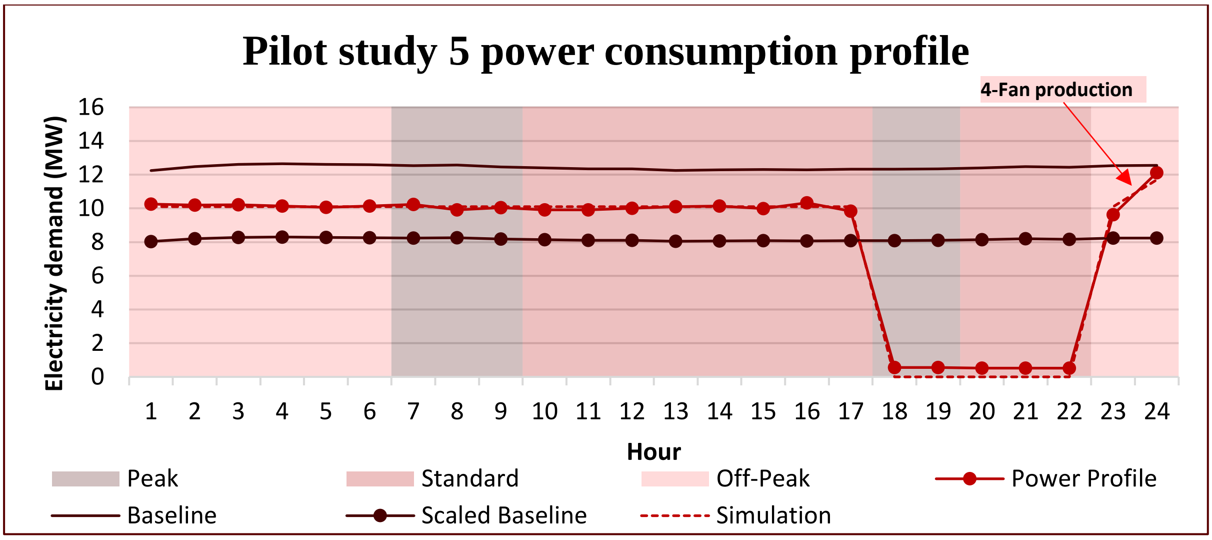

Figure 54: Power consumption profile for pilot study 5

The financial impact is calculated based on the electricity tariffs stated in Table 16. Table 18 provide a comparison between the simulation and actual results. The results showed a percentage difference of less than 10% of the actual values and thereby prove the validity of the simulation. Table 18 provides a breakdown of the electricity cost savings for the pilot studies.

Table 17: Comparison between simulation and pilot study results

	Simulation		Actual		% Diff
	Consumption	Expenditure (R)	Consumption	Expenditure (R)	
Pilot study 1	277 000	R 246 000	280 000	251 000	1.99
Pilot study 2	192 000	R 170 000	196 000	175 000	2.86
Pilot study 3	192 000	R 170 000	177 000	160 000	-6.25
Pilot study 4	192 000	R 170 000	192 000	172 000	1.16
Pilot study 5	194 000	R 171 000	196 000	174 000	1.72

Table 18: Pilot study savings

	Scaled baseline		Actual		Saving (R)
	Consumption (kwh)	Expenditure (R)	Consumption (kWh)	Expenditure (R)	
Pilot study 1	280 000	281 000	280 000	251 000	29 000
Pilot study 2	196 000	197 000	196 000	175 000	22 000
Pilot study 3	177 000	177 000	177 000	160 000	17 000
Pilot study 4	192 000	192 000	192 000	172 000	20 000
Pilot study 5	196 000	197 000	196 000	174 000	23 000
				Total:	111 000

With a total saving of R111 000 on the five days, the initiative proved to be feasible. It must be noted that plant personnel were concerned about the number of fan stop- starts as the large level of inertia causes strain on the fan motor during start-up. This problem can be overcome by installing VSDs on fan motors.

Typical VSDs of this size are unfortunately extremely expensive. This raises the concern that the implementation of production scheduling would require additional capital expenditure. As a result, this alternative might not remain the most feasible initiative for implementation.

In Section 2.5.3 it was noted that applications can be made to Eskom for funding any DSM projects which will reduce electricity demand. A successful application was made to Eskom for the project and the allocated amount covers the full capital outlay for the VSDs. As a result, the capital requirement barrier remains unchanged.

The cost saving initiative evaluation model highlighted the sinter production scheduling to be the most feasible initiative for implementation. This section explained the implementation of the most feasible cost saving initiative. The second and third rated initiatives according to this cost saving initiative evaluation model were *sinter quality optimisation* and *automated sinter control*.

The intention of the sinter quality optimisation initiative was to utilise higher quality raw materials. The investigation between the quality of the current raw materials and that available from alternative suppliers revealed that the current materials are already of the highest available quality.

The third initiative was to automate the *COG* feed into the ignition hood. Investigations indicated that Sinter plant A has already automated the gas feed to the ignition hood. As a result, no further action on this initiative was required.

The purpose of this cost saving initiative evaluation model was to assist management to evaluate potential cost saving initiatives and identify the most feasible alternative for implementation. The short term realisation of actual cost savings resulting from the implementation validates the developed evaluation model as it has fulfilled its purpose.

4.6 Conclusion

The energy cost saving initiative evaluation model was used to identify and prioritise possible saving initiatives on Sinter plant A. The model identified a potential load shift opportunity resulting from the optimisation of the production schedule. The intention of the optimisation was to reduce electricity utilisation during expensive peak tariff periods thereby reducing the electricity cost of the plant whilst maintaining existing sinter production rates.

A simulation was developed to investigate the feasibility of optimising the production schedule by performing a monthly load shift. The simulation highlighted a minimum cost saving opportunity exceeding R1 million over a 3-month period.

After presenting the savings possibilities to the plant personnel at Sinter plant A, approval was obtained for conducting five pilot studies. The five pilot studies, over a period of five days, were conducted and yielded a total saving of R111 000.

5. Conclusion and recommendations.

In this final chapter, the key aspects and results are reviewed and further recommendations for future studies are discussed.

5.1 Revision of research objectives

The first chapter explained that cheap Chinese steel is flooding the global market. As a result, all other steel producers are under pressure to reduce production cost and remain competitive. South African steel producers are part of this global community and need to identify and implement immediate measures for remaining competitive, both in the local and international markets.

The objective of this study was to develop a method that can assist steel producers to identify and evaluate the feasibility of potential cost saving initiatives. Studies indicated that adjustments earlier during the iron and steel production process would render the best results. Raw material preparation and especially the sintering process was identified as the best processes for investigation. The study, therefore, focussed on the sintering process as a small improvement in the sintering process could lead to significant downstream cost savings.

The literature review assisted with a better understanding of the sintering process. Energy efficiency-, process optimisation- and process scheduling initiatives were all investigated for implementation. The investigation was further extended to determine the barriers guiding the implementation of cost saving initiatives. Project evaluation models and project investigation methodologies from literature were also reviewed for further insights.

An initiative evaluation model was developed to assist with the selection of the most feasible initiatives in the shortest possible time. The initiative evaluation model incorporates all important barriers identified by the literature study. Matrices are used to evaluate each initiative. The importance of each of the different barriers and considerations are incorporated by multiplying various factors. The values of these factors were selected, based on the results and considerations from literature.

The methodology was further extended to assist with more detailed investigations after the evaluation model identified the most appealing initiatives. Baseline development and simulation steps were provided to assist with further, more detailed investigations.

5.2 Summary of findings

The proposed cost saving initiative evaluation model was implemented on a case study sinter plant of a steel production facility in South Africa. The cost saving initiative evaluation model was used to identify and prioritise the possible savings initiatives on the sinter plant. The model identified a potential load shift opportunity by optimising the production schedule.

A Microsoft Excel simulation was developed to investigate the feasibility of the load shift opportunity. The simulation used a three-month baseline period and showed that a saving of more than R1 million was possible. Five pilot studies were conducted over five days and a total saving of R111 000 was achieved during these studies.

5.3 Limits and recommendations

The aim for this evaluation model is to provide a quick and easy result to shortlist a few cost saving initiatives. However, the amount of information available, limits the accuracy of the outcomes from the evaluation model. This implies that more accurate results can be obtained with more iterations of the evaluation model as more refined and detailed information is gathered.

Analysing the second and third evaluated initiatives showed that they were not the second and third most feasible initiatives for implementation. However, the short term realisation of actual cost savings after the utilisation of the evaluation model and implementing the most feasible initiative, validated the evaluation model.

For a more accurate outcome, it is recommended that more than one iteration of the initiative evaluation model is required. Further studies should also incorporate an option where not capable of implementation.

In most cases steel production facilities will recruit energy savings or efficiency improvement consulting companies where the consulting company should provide them with cost saving initiatives. It is required that all the possible cost savings initiatives should be considered and short listed. The developed initiative evaluation model can be utilised to initially shortlist a few potentially feasible initiatives.

Discussing the shortlisted initiatives with the steel production facility will highlight important aspects or concerns that should be addressed. Improved results can be obtained by doing a second or even a third iteration of the initiative evaluation while incorporating the latest concerns and information gathered from plant management’s feedback.

During the discussion for permanent implementation of production scheduling certain concerns were raised. Plant personnel was concerned about the amount of stop-starts of the sinter plant fans. Significant strain is present during the starting of the large fans due to the large amounts of inertia. The implementation of soft starters and VSDs will eliminate the problem.

In the case where external funding was not possible, a second iteration of the initiative evaluation model would have lowered the *IR* and put the production scheduling lower on the initiative ratings list. For this study, the utilisation of external funding improved the *IR* to remain amongst the top rated initiatives for funding.

Further studies should focus on developing a method to divide the criteria parameters into more detailed parameters. One of the benefits from the existing method is the simplicity and the challenge will be to continue using simplistic criteria. Different funding methods or tax incentives should also be incorporated into the improved evaluation criteria.

The evaluation model developed in this study can be used for project identifications and evaluations on different plants or industries. The barriers and constraints that were considered are universal and can be applicable on projects even outside the steel industry.

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Appendix A

Initiative:	**Oxygen and Fuel Enrichment**		
Multiplier prioritisation (*MP*):	16	$MP = M_{PI} + M_{ECR} + M_U + M_C$	
	Rating	**Description**	**Comment**
Previous implementation (M_{PI}):	5	No implementation or investigation	Oxygen and fuel enrichment is not implemented or investigated before.
Energy cost ratio (M_{ECR}):	5	Equipment energy cost >10% of total plant energy cost	It is expected that oxygen and fuel enrichment will improve the fuel rates for coke oven gas, coke and anthracite.
Utilisation and availability (M_U):	5	Critical equipment, primary equipment with backup	Oxygen and fuel enrichment will always improve the fuel rates when the plant is in operation.
Capital required (M_C):	1	High capital project	No oxygen lines are present to supply the sinter plant with oxygen. New oxygen lines will have to be installed.
Barrier evaluation (*BE*):	26	$BE = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Su}$	
	Rating	**Description**	**Comment**
Product quality (Q_S):	1	Small improvement on sinter quality.	Small improvements on sinter quality are expected when better combustion takes place.
Payback period (P_{PP}):	2	< 12 months	The large reduction in fuel consumption will lead to significant cost savings. Capital investment to implement the initiative will be recovered within 1 year.
Operational effort (E_{op}):	2	New operations require new skills and additional operational efforts.	New operational skills are required to ensure that correct amounts of oxygen are supplied to the process at all times.
Installation/implementation effort (E_{im}):	1	Installation takes place within a month. Significant operational adjustments should be made.	Oxygen lines should be installed to supply oxygen to the ignition hood and the sinter strand. Oxygen flow meters and off gas analysers to monitor the oxygen levels during the process will be required.
Investigation effort (E_{in}):	1	Significant amount of investigation required. Most of the required data is available for investigations.	Off gas analysers installed in wind boxes below the sinter bed will assist with the investigation process. Safety risks involving oxygen should be further investigatigated to determine the safe levels of oxygen that can be
Sustainability (S_{sus}):	2	Small amounts of maintenance required on a regular basis. Optimised operations are sustainable with little effort.	If process operators are familiar with the new operations, the operations will be sustainable. Maintenance procedures to ensure that oxygen analysers are fully functional, will have to be set in place.
Initiative rating (*IR*):	30.59	$IR = \frac{MP \times BE}{IR_{Max}} \times 100$	

Initiative:	**Segregated Material Charging**		
Multiplier prioritisation (*MP*):	11	$MP = M_{PI} + M_{ECR} + M_U + M_C$	
	Rating	**Description**	**Comment**
Previous implementation (M_{PI}):	0	Successful implementation	A segregated material charging chute is already installed and works effectively.
Energy cost ratio (M_{ECR}):	5	Equipment energy cost >10% of total plant energy cost	Segregated material charging will improve the fuel rates for coke and anthracite.
Utilisation and availability (M_U):	5	Critical equipment, primary equipment with backup	Raw material charging is a key step in the sintering process.
Capital required (M_C):	1	High capital project	Literature showed that far more than R1 million is required to improve material charging equipment.
Barrier evaluation (*BE*):	28	$BE = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Su}$	
	Rating	**Description**	**Comment**
Product quality (Q_S):	2	Large improvement on sinter quality.	Better granule size distributions will account for significant improvements on sinter quality.
Payback period (P_{PP}):	0	> 24 months	It is shown from literature that the payback period is approximately 2.4 years.
Operational effort (E_{op}):	4	No new operational skills required.	New equipment will replace the previous charging equipment and no new operational skills are required.
Installation/implementation effort (E_{im}):	1	Installation takes place within a month. Significant operational adjustments should be made.	A new and improved charging chute should be installed to improve the present material charging method.
Investigation effort (E_{in}):	2	Fair amount of investigation required. Most of the required data is available for investigations.	Chemical analyses and breakdown of the chemical process will be required to quantify the potential improvement in sinter quality and production. Weigh feeders are already used to measure and charge the correct
Sustainability (S_{sus}):	2	Small amounts of maintenance required on a regular basis. Optimised operations are sustainable with little effort.	New maintenance procedures should be in place to monitor and remove material blockages that occur with the new charging equipment.
Initiative rating (*IR*):	22.65	$IR = \frac{MP \times BE}{IR_{Max}} \times 100$	

Initiative:	**Production Scheduling**		
Multiplier prioritisation (MP):	17	$MP = M_{PI} + M_{ECR} + M_U + M_C$	
	Rating	**Description**	**Comment**
Previous implementation (M_{PI}):	3	Successful implementation, not sustained	Plant personnel showed from historical data that sinter production was scheduled before.
Energy cost ratio (M_{ECR}):	5	Equipment energy cost >10% of total plant energy cost	Sinter production is expected to reduce electricity costs. Electricity costs comprise more than 10% of the total energy costs on the sinter plant.
Utilisation and availability (M_U):	4	Alternate between equipment regularly	Plant operations alternate between fans regularly by switching them on and off.
Capital required (M_C):	5	No capital required	No new equipment or equipment adjustments are required, therefore no capital is required.
Barrier evaluation (BE):	41	$BE = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Su}$	
	Rating	**Description**	**Comment**
Product quality (Q_S):	0	Does not affect the sinter quality.	It is expected that the sinter quality will not be affected when the production is scheduled for different time periods.
Payback period (P_{PP}):	4	< 3 months	The payback period is less than 3 months as no capital is required.
Operational effort (E_{op}):	3	New operations require minimum new skills, but no additional effort.	Operators are expected to follow new production schedule.
Installation/implementation effort (E_{im}):	4	No installation required. Only operational or scheduling adjustments required for implementation.	No new equipment should be installed. A new optimised production schedule can be implemented immediately.
Investigation effort (E_{in}):	3	Minimal investigation required. Most of the required data is available for investigations.	Production, stock levels, electricity consumption and sinter quality are already monitored. The capacity to move production should be investigated.
Sustainability (S_{sus}):	1	Maintenance required on a regular basis. Optimised operations are sustainable with descent effort.	Efforts to develop the best possible production schedule will be required each month. More maintenance is required when equipment is switched on and off more regularly.
Initiative rating (IR):	51.25	$IR = \frac{MP \times BE}{IR_{Max}} \times 100$	

Initiative:	**Automated Sinter Control**		
Multiplier prioritisation (*MP*):	13	$MP = M_{PI} + M_{ECR} + M_U + M_C$	
	Rating	**Description**	**Comment**
Previous implementation (M_{PI}):	0	Successful implementation	A system to control the ignition hood temperature is already installed. The ignition hood temperature setpoint is set and the gas flow is automatically adjusted accordingly.
Energy cost ratio (M_{ECR}):	3	Equipment energy cost <5% of total plant energy cost	Automated control adjusts the gas flow for optimal ignition hood temperature. Coke oven gas is a small contributer towards the total energy cost of the plant.
Utilisation and availability (M_U):	5	Critical equipment, primary equipment with backup	The ignition hood is required for coke and anthracite combustion during sinter production.
Capital required (M_C):	5	No capital required	Thermocouples are already installed and the required capital for a control system is negligibly small.
Barrier evaluation (*BE*):	42	$BE = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Su}$	
	Rating	**Description**	**Comment**
Product quality (Q_S):	0	Does not affect the sinter quality.	A constant ignitionhood temperature is expected to assist with a more constant sinter quality, but the sinter quality is not expected to change.
Payback period (P_{PP}):	4	< 3 months	The payback period is less than 3 months as the required capital negligibly small.
Operational effort (E_{op}):	4	No new operational skills required.	New control system will automatically control the gas flow rates to maintain a more constant ignitionhood temperature.
Installation/implementation effort (E_{im}):	2	Installation can be done within 24 hours. Implementation can be done with small operational adjustments.	New operational controls and control systems should be added to the existing system. From literature it was seen that this installation setup can be done within 24 hours.
Investigation effort (E_{in}):	3	Minimal investigation required. Most of the required data is available for investigations.	Minimal investigation is required. All the required measurements are already in place. Additional control systems should be added to the SCADA system.
Sustainability (S_{sus}):	3	Operation seldom requires maintenance. Optimised operations are easy to sustain.	The new system will be sustainable as the control system is adjusted permanently.
Initiative rating (*IR*):	40.15	$IR = \frac{MP \times BE}{IR_{Max}} \times 100$	

Initiative:	**Sinter Bed Optimisation**		
Multiplier prioritisation (*MP*):	12	$MP = M_{PI} + M_{ECR} + M_U + M_C$	
	Rating	**Description**	**Comment**
Previous implementation (M_{PI}):	1	Previous investigation, negative attitude	Sinter bed optimisation was previously investigated and according to the plant personnel they have the expertise to optimise the sinter bed properties among themselves.
Energy cost ratio (M_{ECR}):	5	Equipment energy cost >10% of total plant energy cost	Sinter bed optimisation can improve coke, anthracite and electricity consumption.
Utilisation and availability (M_U):	5	Critical equipment, primary equipment with backup	The sinter bed mixture is the raw material input necessary for sinter production.
Capital required (M_C):	1	High capital project	Sinter bed depth is already at a maximum. For further adjustments, equipment should be replaced.
Barrier evaluation (*BE*):	18	$BE = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Su}$	
	Rating	**Description**	**Comment**
Product quality (Q_S):	-1	Slight reduction in sinter quality.	Increasing the sinter bed depth will improve the production rate, but the bed permeability is reduced which causes a reduction in sinter quality.
Payback period (P_{PP}):	1	< 24 months	A payback period of approximately 1.6 years is reported in literature.
Operational effort (E_{op}):	4	No new operational skills required.	The new charging equipment is operated in the exact same way as the previous equipment.
Installation/implementation effort (E_{im}):	1	Installation takes place within a month. Significant operational adjustments should be made.	The charging chute will need to be replaced to accommodate a deeper sinter bed depth. This installation will require the sintering process to be stopped completely until the equipment is replaced.
Investigation effort (E_{in}):	1	Significant amount of investigation required. Most of the required data is available for investigations.	The strand speed and strand dimensions are available. The expected change in sinter quality require detailed analysis by highly skilled metallurgists.
Sustainability (S_{sus}):	3	Operation seldom requires maintenance. Optimised operations are easy to sustain.	The new system will be sustainable as the new charging equipment is premanently installed.
Initiative rating (*IR*):	15.88	$IR = \frac{MP \times BE}{IR_{Max}} \times 100$	

Initiative:	**Reduce Air Leakage**		
Multiplier prioritisation (MP):	14	$MP = M_{PI} + M_{ECR} + M_U + M_C$	
	Rating	**Description**	**Comment**
Previous implementation (M_{PI}):	3	Successful implementation, not sustained	Air leakages are repaired continuously. Better maintenance procedures may improve sustainability.
Energy cost ratio (M_{ECR}):	3	Equipment energy cost <5% of total plant energy cost	Air leakage reduction reduces false air and electricity costs. Electricity costs comprise more than 10% of the total energy costs on the sinter plant.
Utilisation and availability (M_U):	5	Critical equipment, primary equipment with backup	Suction in fan ducting is required for draft air to be drawn in through the sinter bed.
Capital required (M_C):	3	Low capital project	Maintenance and replacement parts on damaged fan ducting will require small amounts of capex.
Barrier evaluation (BE):	22	$BE = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Su}$	
	Rating	**Description**	**Comment**
Product quality (Q_s):	0	Does not affect the sinter quality.	Repairing the air leakages will increase the productivity of the plant, but the product quality is expected to remain unchanged.
Payback period (P_{PP}):	1	< 24 months	The payback period is very site specific, but from literature it is reported to be in the order of approximately 1.3 years.
Operational effort (E_{op}):	3	New operations require minimum new skills, but no additional effort.	Better maintenance skills are required for more effective maintenance on fan ducting. More active maintenance routines for identifying and repairing air leakages will also require additional maintenance time.
Installation/implementation effort (E_{im}):	2	Installation can be done within 24 hours. Implementation can be done with small operational adjustments.	Air leakage repairs and maintenance procedures are in place. Additional equipment and replacement parts to reduce air leakages can be installed during maintenance stops.
Investigation effort (E_{in}):	3	Minimal investigation required. Most of the required data is available for investigations.	Air leakages are monitored on the SCADA. Oxygen analysers are in place in the fan ducting. The quantification of false air through the sinter bed will require further investigation.
Sustainability (S_{sus}):	1	Maintenance required on a regular basis. Optimised operations are sustainable with descent effort.	Additional efforts and procedures should be set in place to monitor and improve sustainability.
Initiative rating (IR):	22.65	$IR = \frac{MP \times BE}{IR_{Max}} \times 100$	

Initiative:	**Sinter Quality Optimisation**		
Multiplier prioritisation (*MP*):	16	$MP = M_{PI} + M_{ECR} + M_U + M_C$	
	Rating	**Description**	**Comment**
Previous implementation (M_{PI}):	1	Previous investigation, negative attitude	Sinter quality optimisation was previously investigated and according to the plant personnel further quality improvements can only happen if better raw materials are available.
Energy cost ratio (M_{ECR}):	5	Equipment energy cost >10% of total plant energy cost	Sinter quality optimisation can improve coke, anthracite and electricity consumption. The energy consumption of the blast furnace will also be reduced when sinter quality is improved.
Utilisation and availability (M_U):	5	Critical equipment, primary equipment with backup	Improving the raw materials required for sinter production will improve quality of the sinter produced during operation.
Capital required (M_C):	5	No capital required	Better quality raw materials are more expensive, but raw material input costs are not regarded as capital expenditure required for project implementations.
Barrier evaluation (*BE*):	41	$BE = w_{SQ}Q_S + w_{PP}P_{PP} + w_{op}E_{op} + w_{im}E_{im} + w_{in}E_{in} + w_{Sus}S_{Su}$	
	Rating	**Description**	**Comment**
Product quality (Q_S):	1	Small improvement on sinter quality.	Best possible quality materials are used for sinter. More expensive improved quality materials will have to be imported.
Payback period (P_{PP}):	4	< 3 months	Improving the raw material sinter mixture to achieve better sinter quality requires no capital and therefore the payback period is less than 3 months.
Operational effort (E_{op}):	3	New operations require minimum new skills, but no additional effort.	Operational personnel should be informed about the optimised material mixtures. Alterations on the raw material mixtures may require different procedures or setpoints during the sintering process.
Installation/implementation effort (E_{im}):	3	Quick and easy installation/implementation within 2 hours. Installation can take place during operation.	Raw material weigh feeders should be updated with the optimised raw material ratios for better sinter quality. No other hardware or equipment alterations are required for implementation.
Investigation effort (E_{in}):	1	Significant amount of investigation required. Most of the required data is available for investigations.	Sinter quality improvements require detailed analysis by highly skilled metallurgists. Time consuming and detailed tests are required to investigate the influence of adjustments on the raw material sinter
Sustainability (S_{sus}):	0	High level maintenance is required. Intense efforts are required for sustainability.	Best available quality materials are used for sinter. A continuous search for cheap alternative high quality materials to be imported will be required.
Initiative rating (*IR*):	48.24	$IR = \frac{MP \times BE}{IR_{Max}} \times 100$	