



Improving energy cost performance of steel production mills

SGJ van Niekerk

 **orcid.org 0000-0003-2688-2884**

Thesis submitted in fulfilment of the requirements for the degree
Doctor of Philosophy in Mechanical Engineering at the
Potchefstroom Campus of the North-West University

Promoter: Dr JH Marais

Examination May 2018

Student number: 22133208

ABSTRACT

Title: Improving energy cost performance of steel production mills
Author: S.G.J. van Niekerk
Supervisor: Dr J.H. Marais
Degree: Doctor of Philosophy in Mechanical Engineering
Keywords: Energy consumption, Optimisation, Reheating furnace, Steel plants

The global steel supply capacity is more than the demand. This has caused an increase in competition and imports to some countries. South Africa is one of the affected countries and the effects have been seen in the closing down of four local steel producers since 2009. The South African iron and steel industry is under immense pressure to reduce operational costs to remain competitive.

Energy consumption contributes about 20% to the operational costs of an integrated steelmaking facility. In the production of steel profiles, the finishing rolling operations are a large energy consumer. These operations consume 20% of the energy in steelmaking. Hot rolling operations are equipped with reheating furnaces that operate on fuel gas. An integrated steelmaking facility produces by-product gases that can be consumed as an energy source throughout the works. Reheating furnaces can be designed to operate on these gases.

When a by-product gas supply shortage occurs, the gas can be supplemented with purchased gases like natural gas. This occurs frequently in the older plants of South Africa. A human operator is responsible for controlling the by-product gases distributed in a complex network throughout the works. Quick reactions are required in this process where changes to the system occur frequently. The operator cannot always distribute the gases optimally based on the energy efficiency of the reheating furnaces. Energy efficiency losses occur that increase the costs of production.

Research has shown that existing furnace simulation and optimisation models do not allow for changes to the gas supply type, as the primary focus is on the control of temperature in the furnace. Optimisation models of the whole facility focus on the complete utilisation of thermal energy or the improvement of production scheduling. Real-time optimisation systems require complex measurements that are often unavailable in older facilities,

therefore, requiring expensive refurbishment of the furnaces. The existing systems do not take into account the effect of other components in the network.

A methodology has been developed in this study that characterises the energy consumption of reheating furnaces. The outcome of the model is to simulate the energy consumption of the furnace under different workloads and the effect of changing fuel supply. These furnace models are configured in a network so that changes to the gas supply can be simulated. This model is then used to develop a real-time optimisation system that can optimise the by-product gas distribution to the reheating furnaces for improved cost performance on purchased gases.

The methodology is validated on a case study steelmaking facility based in South Africa. The facility has five reheating furnaces in four rolling mills. By-product gas is supplemented with natural gas in the case of shortages. The gas consumption for the rolling operations comprised of 38% natural gas and 62% by-product gas for the year 2016. Implementing the optimisation model on historical data indicated a 9% possible reduction in natural gas.

The methodology was validated by implementing the real-time optimisation system for a test period. Results showed daily natural gas consumption improvements of up to 13%. The overall improvement in natural gas consumption was 3% when including all data and 4% when excluding operational restrictions. Based on the natural gas consumption for 2016, the cost saving projection at a 4% natural gas reduction is R 2.3 million per year, excluding other charges.

ACKNOWLEDGEMENTS

I want to thank the Lord Jesus Christ for giving me the ability to complete my studies and providing me with motivation, creativity and peace throughout my life. Without His love and guidance, I would not have succeeded.

To my parents and brother, Sybrand, Hannelie and Henri van Niekerk: Thank you for your unconditional love, support and encouragement during my studies. Without you, I would never have had the opportunity to complete this thesis.

To the Doctors, Janco Vermeulen, Johan Marais, Marc Mathews and Wynand Breytenbach, thank you for your valuable inputs and guidance during the writing of this thesis. To all my friends and colleagues, thank you for the valuable inputs, guidance and support.

To the Professors, Eddie Mathews and Marius Kleingeld, thank you for giving me the opportunity to complete my PhD degree at CRCED Pretoria. I would like to thank TEMM International and Enermanage for the opportunity, financial assistance and support to complete this study.

TABLE OF CONTENTS

Abstract	I
Acknowledgements	III
Table of contents	IV
List of figures	VI
List of tables	VIII
List of abbreviations	IX
List of symbols	X
List of units	XI
1 Introduction	1
1.1 Preamble	2
1.2 Market challenges in the steel industry	2
1.3 Typical energy consumption in the steel industry	4
1.4 Background on steel production facilities	5
1.5 Overview of fuel gases in steel production	11
1.6 Research motivation and objective	14
1.7 Novel contributions of the study	15
1.8 Overview of thesis	18
1.9 Summary	19
2 Literature review	20
2.1 Preamble	21
2.2 Energy modelling of reheating furnaces	22
2.3 Optimisation of reheating furnaces	33
2.4 Real-time optimisation models	46
2.5 Summary	53
3 Methodology	56
3.1 Preamble	57
3.2 Furnace energy characterisation model	57
3.3 Gas distribution network optimisation model	66
3.4 Real-time gas distribution optimisation system	70
3.5 Optimisation system benefit quantification method	73
3.6 Summary	77

4	Validation through case study	78
4.1	Preamble	79
4.2	Case study information	79
4.3	Implementation of furnace characterisation models	86
4.4	Application of the distribution optimisation model	93
4.5	Implementation of the real-time optimisation system	95
4.6	Verification of real-time optimisation system	97
4.7	Discussion of results	104
4.8	Summary	106
5	Conclusion	108
5.1	Review of work completed	109
5.2	Recommendations	111
6	References	112
Appendix A	Detail results	119

LIST OF FIGURES

Figure 1-1: World steel production in 2016, adapted from World Steel Association [1]	2
Figure 1-2: South African steel production, imports and exports for 2007-2016 [4]	3
Figure 1-3: Sectorial primary energy consumption of industry in South Africa for 2015 [7]	4
Figure 1-4: Steel production routes, adapted from World Steel Association	6
Figure 1-5: Overview of the hot rolling process, adapted from The Institute for Industrial Productivity	9
Figure 1-6: Section view of a walking beam type reheating furnace, adapted from Kyungdong Worldwide	10
Figure 1-7: By-product and natural gas distribution network	13
Figure 2-1: Literature review overview	21
Figure 2-2: Overview of research on reheating furnace energy modelling	22
Figure 2-3: Overview of research on whole facility and reheating furnace optimisation	33
Figure 2-4: Overview of research on real-time optimisation models	46
Figure 3-1: Basic layout of a reheating furnace	57
Figure 3-2: Daily furnace energy consumption vs production	59
Figure 3-3: Furnace daily gas consumption flow	60
Figure 3-4: Daily furnace energy consumption vs production for differing by-product gas mixtures	61
Figure 3-5: Furnace gas consumption per hour vs COG in the mixture	62
Figure 3-6: Maximum furnace gas consumption per hour vs COG in the mixture	63
Figure 3-7: Reheating furnace energy simulation example	65
Figure 3-8: Basic gas supply and consumer layout	66
Figure 3-9: Flow diagram of the gas optimisation model	69
Figure 3-10: Actual network gas distribution and mixtures	72
Figure 3-11: Suggested network gas distribution and mixtures	72
Figure 3-12: Example of the optimised average natural gas consumption for a gas network	74
Figure 4-1: Plant layout of case study	79
Figure 4-2: Mill 1 reheating furnaces	81

Figure 4-3: Mill 2 reheating furnace _____	81
Figure 4-4: Mill 3 reheating furnace _____	82
Figure 4-5: Mill 4 reheating furnace _____	83
Figure 4-6: Plant production output for 2016 _____	84
Figure 4-7: Mill gas consumption figures for 2016 _____	84
Figure 4-8: Mill 1 furnace 1 energy per hour characterisation model _____	87
Figure 4-9: Mill 1 furnace 2 energy per hour characterisation model _____	87
Figure 4-10: Mill 2 furnace energy per hour characterisation model _____	88
Figure 4-11: Mill 3 furnace energy per hour characterisation model _____	88
Figure 4-12: Mill 4 furnace energy per hour characterisation model _____	89
Figure 4-13: Mill 3 furnace characterisation model verification – Temperatures _____	92
Figure 4-14: Mill 3 furnace characterisation model verification – 5-minute interval data _____	92
Figure 4-15: Plant energy consumption and optimisation results for the scoping period _____	94
Figure 4-16: Real-time optimisation system dashboard _____	96
Figure 4-17: First implementation period optimisation results _____	97
Figure 4-18: Second implementation period optimisation results _____	98
Figure 4-19: Baseline period optimisation results _____	100
Figure 4-20: Baseline period averaged optimisation results _____	100

LIST OF TABLES

Table 3-1: Actual and suggested gas flow distribution changes _____	72
Table 3-2: Example of the gas network configurations of two furnaces _____	75
Table 3-3: Example of the grouped natural gas lost opportunity of a furnace network ___	75
Table 4-1: Plant furnace zones and fuel types _____	85
Table 4-2: Plant fuel gas energy constants _____	86
Table 4-3: Furnace energy per hour characterisation regression models _____	90
Table 4-4: Mill 3 furnace burner configurations for verification _____	91
Table 4-5: Plant energy consumption and optimisation results of the scoping period ___	95
Table 4-6: Possible furnace operational status configurations _____	101
Table 4-7: Baseline period lost energy savings opportunity for furnace configurations _	102
Table 4-8: Natural gas price for South Africa grouped by annual gas consumption [78]	103
Table 4-9: Implementation period results _____	104
Table A-1: Mill production figures for 2016 _____	119
Table A-2: Mill gas consumption figures for 2016 _____	119

LIST OF ABBREVIATIONS

BF	Blast Furnace
BFG	Blast Furnace Gas
BOF	Basic Oxygen Furnace
CFD	Computational Fluid Dynamics
CIS	Commonwealth of Independent States
COG	Coke Oven Gas
DR	Direct Reduction
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
GUI	Graphical User Interface
MILP	Mixed integer linear programming
SL/RN	Stelco-Lurgi / Republic Steel-National Lead

LIST OF SYMBOLS

c	Intercept of regression model
CV	Calorific Value
E	Energy
E_{Actual}	Furnace energy lost opportunity actual
E_{Baseline}	Furnace energy lost opportunity baseline
E_{Load}	Furnace energy consumption at specified load
E_{Maximum}	Furnace energy consumption at maximum load
$\text{Load}_{\text{Furnace}}$	Percentage furnace work load
m	Slope of regression model
\dot{V}	Volumetric flow
x	Independent variable of regression model

LIST OF UNITS

GJ	Gigajoule
GJ/a	Gigajoule per annum
GJ/h	Gigajoule per hour
J	Joule
kt	Kilotonne
m ³	Cubic meter
m ³ /h	Cubic meters per hour
MJ	Megajoule
MJ/m ³	Megajoule per cubic meter
Mt	Megatonne
PJ	Petajoules
R	South African Rand
R/GJ	South African Rand per GJ
TJ	Terajoule
t	Tonne

1 INTRODUCTION



Ladle charging hot steel into the Basic Oxygen Furnace. ¹

¹ Siemens VAI, "Steelmaking Automation," 2007.

1.1 Preamble

In this chapter an overview of the challenges faced in the iron and steel industry is provided. Background on integrated steelmaking facilities and their energy consumption is discussed. The motivation and objective of the study are provided. Finally, the novel contributions of this research are summarised.

1.2 Market challenges in the steel industry

1.2.1 WORLD STEEL PRODUCTION

World steel production is an indication of global development. The world total production of crude steel amounted to 1 630 million tonnes [t] in 2016. The global production share of steel per region is shown in Figure 1-1. China has a clear dominance over the market with a 49.6% share of the total crude steel production [1].

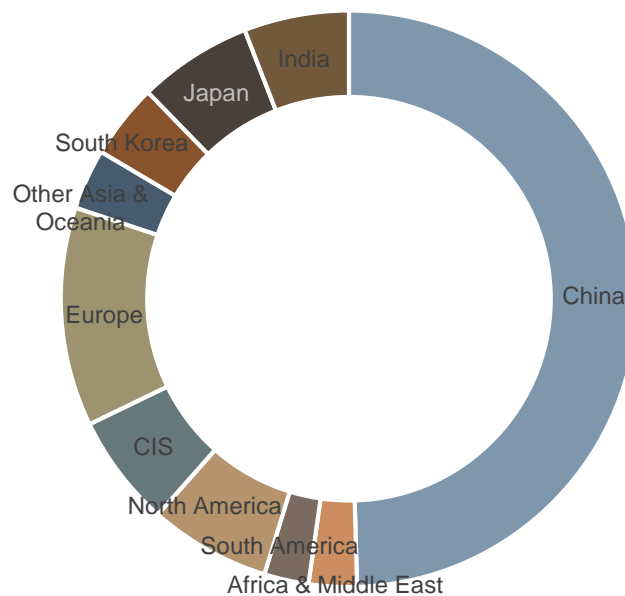


Figure 1-1: World steel production in 2016, adapted from World Steel Association [1]

The global steel supply capacity is more than the current demand. China accounts for more than a third of this steel oversupply [2]. This has had the effect of increasing steel imports in other countries in what is described as unfair competition. This has placed other countries' steel sectors, and the jobs linked to it, under significant pressure [3].

The figures published by the World Steel Association ranks South Africa in 24th position global steel production. The crude steel production for 2016 was 6.1 million tonnes. South Africa is the largest steel producer in Africa [1].

1.2.2 SOUTH AFRICAN STEEL MARKET CONDITIONS

South Africa has been affected by the increase in global steel exports. Figure 1-2 indicates the South African iron and steel imports for the period 2007 to 2016. Steel imports have more than doubled from a low in 2009 to 1 392 million tonnes in 2016 according to figures published by the World Steel Association [4]. This has put additional strain on local South African steel producers to remain competitive.

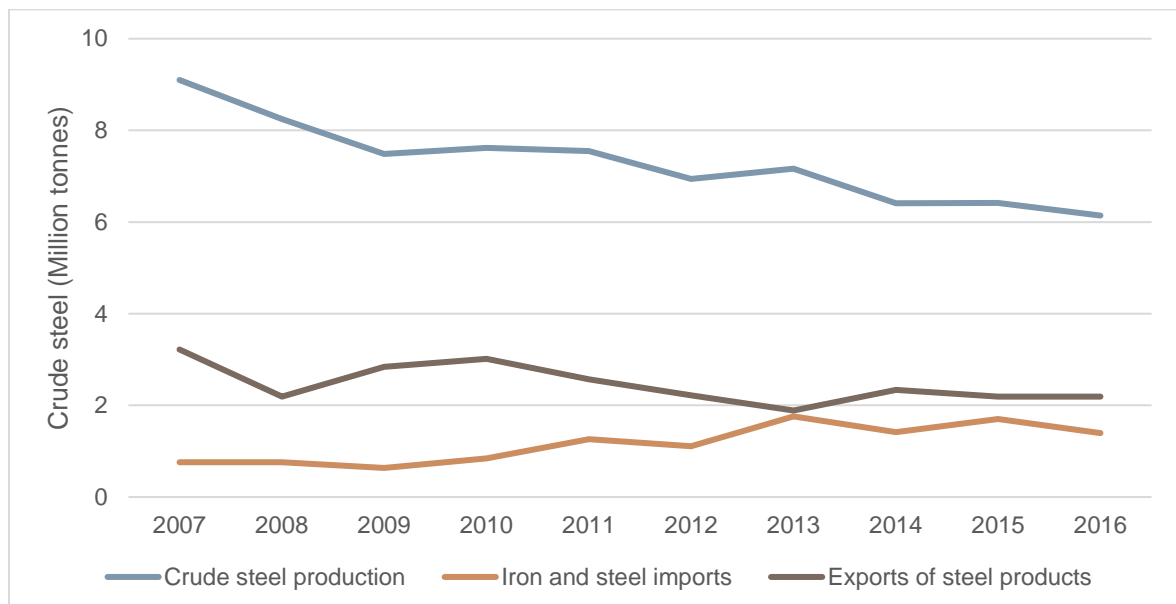


Figure 1-2: South African steel production, imports and exports for 2007-2016 [4]

What is alarming, is the almost one-third decrease in crude steel production, shown in Figure 1-2, from a high in 2007 to 6 141 million tonnes produced in 2016 [4]. If this trend were to continue, South Africa's iron and steel industry would disappear within two decades, as was suggested in a study by Dondofema et al. Quality and affordable steel imports pose a great threat to the industries' continued existence [5].

Another problem accompanying the increase in steel imports, is the decrease in steel exports also shown in Figure 1-2. The figure has decreased from a high in 2007 by almost a third, to 2 194 million tonnes in 2016. This is closely related to the decrease in crude steel production. Although, it does seem that the trend has stabilised for the last three years [4].

“Local steel producers face immense competition, and the results are inevitable: CISCO stopped operations in 2009, as did the AMSA Vanderbijlpark mini-mill plant in 2012 and the AMSA Vereeniging mini-mill plant in 2015; and EVRAZ HSVC closed its doors in 2016” [5].

Steel production facilities need to reduce their operational costs to remain competitive under these extremely difficult market conditions. The iron and steel industry is one of the most energy-intensive industries, consuming energy carriers like coal, electricity, heavy oil, natural gas and by-product gases. The energy consumption of steel facilities contributes to about 20% of the total operational costs [6]. A breakdown of energy consumption in the steel industry follows.

1.3 Typical energy consumption in the steel industry

1.3.1 INDUSTRIAL SECTOR ENERGY CONSUMPTION IN SOUTH AFRICA

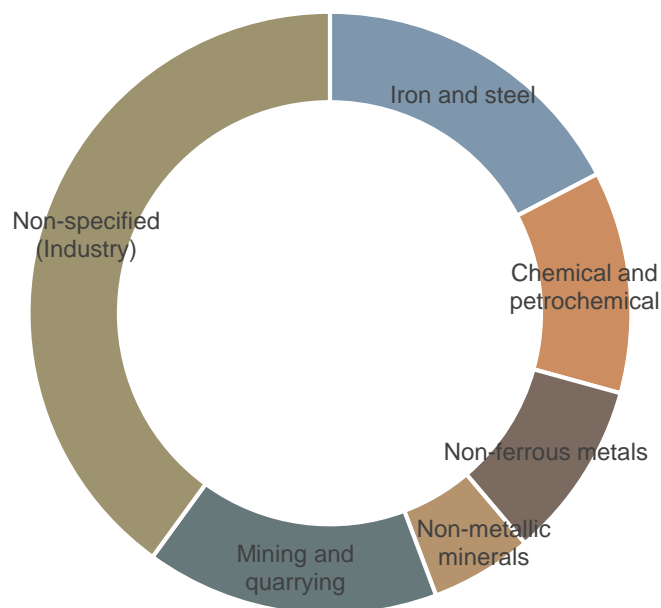


Figure 1-3: Sectorial primary energy consumption of industry in South Africa for 2015 [7]

This section provides an overview of the typical energy consumption in the steel industry. A breakdown of the primary energy consumption of South Africa’s industrial sector is shown in Figure 1-3. The total primary energy consumed by industry amounted to 1 173 petajoules [PJ] in 2015 according to the South African Department of Energy [7]. The

iron and steel industry makes up the largest portion of industrial energy consumption at 204 PJ or 17%. Closely followed by the mining sector at 16%, the chemical and petrochemical industry at 12% and the non-ferrous metal sector at 10% [7].

Energy costs in the steel industry is a large contributor to operational costs. Improving energy efficiency in the steelmaking sector is imperative to ensure the competitiveness of the industry [8]. Additionally, to address climate change, the South African government has committed to reduce greenhouse gas emissions by 34% by 2020 and 42% by 2025 as has been published in various new government regulations [9]. This has placed further stress on industry to reduce energy consumption and the emissions that accompany with it.

1.3.2 ENERGY CONSUMPTION IN STEEL FACILITIES

The iron and steel industry is an energy intensive, high pollution and high emission sector [10]. Around the world, the iron and steel industry accounts for approximately 5% of the global total CO₂ emissions [10]. Globally the sector is an important subject of research for the reduction of energy consumption and greenhouse gas emissions [11].

Steel production facilities differ in terms of layout and components. There are numerous opportunities for energy and cost reduction on these components. One of the main operational processes is the finishing rolling operations in steel production. The rolling process consumes up to 20% of the energy in an integrated steel facility. In these operations, the main energy consuming component is the reheating furnace, which consumes 70% of the energy in the rolling mills [12]. The reheating furnace is an important topic in research and one of the focus areas of this study. Further background on the components found in the steel industry follows in the next section.

1.4 Background on steel production facilities

1.4.1 OVERVIEW OF THE PRODUCTION PROCESS

This section provides a basic overview of the production process in steel facilities. The focus is placed on the material flow and the energy consumption of the components. Two main steel production routes exist, as shown in Figure 1-4. These routes are the Blast Furnace and Basic Oxygen Furnace (BF-BOF) route, as well as the Electric Arc Furnace (EAF) route [8]. Many different components and variations of this process exist.

Approximately 70% of steel producers use the BF-BOF route [8]. Steel is produced from raw materials such as iron ore, coal, fluxes and recycled steel. All steel contains recycled steel since steel demand cannot be met with the BF-BOF route alone [8].

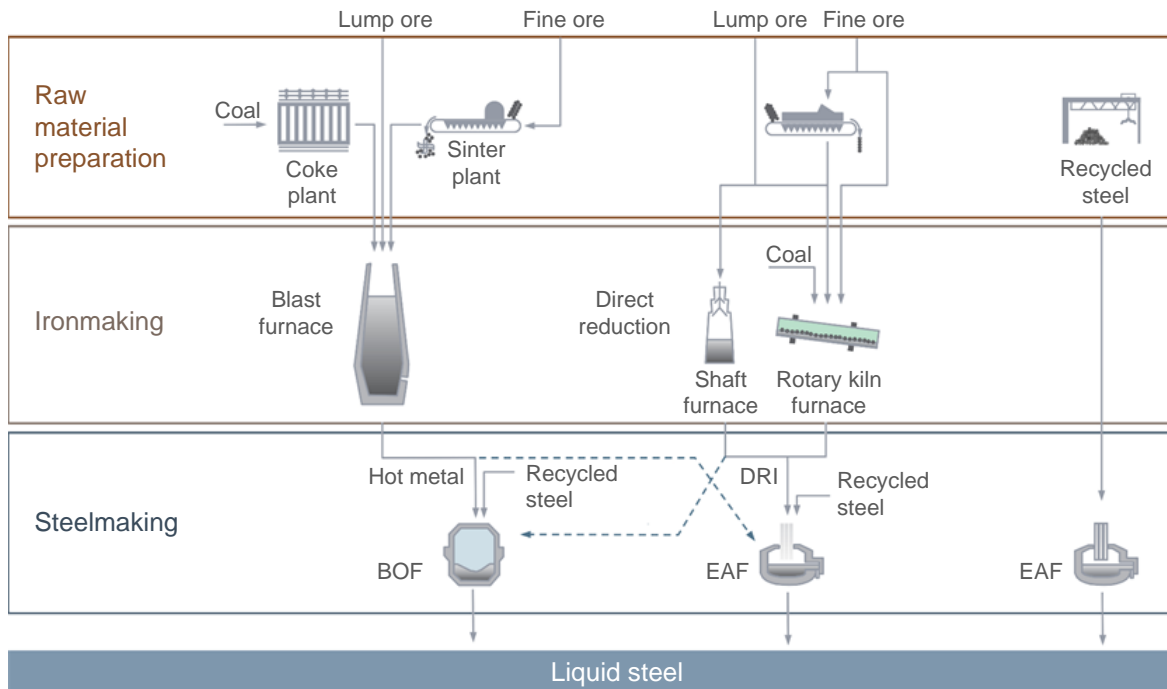


Figure 1-4: Steel production routes, adapted from World Steel Association ²

The process starts with iron ore which is melted in the blast furnace to produce hot metal which is reduced in the BOF to produce liquid steel and is cast in various shapes. In the EAF route, recycled steel is melted in an electric arc furnace. 29% of steel is produced via this route [8]. Direct Reduced Iron (DRI) can be used to supplement recycled steel. The liquid steel is then alloyed to achieve the desired composition. After this the steel is rolled into sheets, coils, sections or bars [8]. More detail on the energy consumption and process overview of the components follow in this section.

1.4.2 RAW MATERIAL PREPARATION

Coke making

The first part of the process is raw material preparation. Coke production is the first step discussed. Coke is one of the main raw materials and sources of energy used in iron production with the BF-BOF route. Coke provides the thermal energy and acts as a reducing

² World Steel Association, "Energy use in the steel industry," 2014.

agent for iron production. Coke is produced by heating coal in coke ovens for several hours to drive off the volatiles and moisture in the coal. The process produces by-products, notably Coke Oven Gas (COG), that can be used as a fuel source in the plant [13], [14].

Sinter plant

Another step in raw material preparation is sinter making. Sinter improves the reduction process in the blast furnace to reduce coke demand thereby reducing energy consumption in the energy intensive blast furnace. It is produced in a sinter plant from a blend of fine iron ore, fluxing agents and coke particles. The blend is ignited with an ignition hood, that operates on fuel gas, and air is sucked through the mixture to enable combustion. The particles are sintered together after which the material is cooled, crushed and screened for use in the blast furnace [13]–[15].

1.4.3 OVERVIEW OF IRON MAKING PROCESSES

Blast furnace

Ironmaking is the next part of the steel production process, with the blast furnace being one of the main components. The blast furnace produces iron from a blend of iron-containing materials, coke and fluxes. The burden is charged in the top of the furnace, heated air is blast into the bottom of the furnace along with some form of liquid, gaseous or powdered fuel. This burns the coke, which is the main energy source, in the furnace to produce the heat for the reduction of oxygen in the iron ore. The iron ore melts and the flux combines with impurities in the iron. The impurities accumulate in slag at the bottom of the shaft. These are separated and the hot metal is sent to a melt shop for casting. The process has a by-product gas that can be used as a fuel source in the plant [16].

Rotary kilns

Another method to produce iron is the direct reduction route. Some plants employ rotary kilns to produce Direct Reduced Iron (DRI) via the Stelco-Lurgi / Republic Steel-National Lead (SL/RN) process. The process can use low-quality coal as energy source along with dolomite or limestone to reduce the iron ore. The charge is reduced to iron oxide in the preheat zone of the kiln. It then passes to the reduction zone where the charge is heated, volatiles are driven off and the carbon in the iron ore is burned off to produce DRI. The process produces residual gas that can be used for electricity generation [16].

Corex process

Another, newer, process that can produce liquid iron is the Corex process. The Corex reduction shaft produces hot metal from lump ore or pellets using non-coking coal as energy source. The Corex shaft consists of two sections. The iron ore is reduced in the reduction shaft and discharged to the melter gasifier where the gasification of coal takes place. The gas produced can be used as a fuel source in the plant. The hot metal produced can be further treated with a BOF or EAF which are discussed next [11], [16].

1.4.4 OVERVIEW OF STEELMAKING PROCESSES

Basic Oxygen Furnace

The next step in the production process is the steelmaking process itself. A key component is the Basic Oxygen Furnace (BOF). The BOF refines the hot metal from the blast furnace or other process into steel by injecting oxygen into the iron to burn off excess carbon. The process is an exothermic reaction that does not require additional energy. The desired product specification is achieved by adding scrap metal and alloys, as well as limestone for slag formation. A by-product gas is formed in the process that is either burned off or can be used for fuel in the plant. The final product specifications are usually achieved by secondary metallurgy processes that follow the BOF process [13], [14], [17].

Electric Arc Furnace

The Electric Arc Furnace (EAF) process is an alternative to the more common BF-BOF steel production route. The primary material in this process is recycled ferrous scrap metal. The furnace can manufacture carbon and alloy steels by melting the product with high-powered electric arcs as the energy source. The goal is to melt the steel as fast as possible and then to refine it further, however, any secondary metallurgical operation can be performed in the EAF as well [14], [17].

1.4.5 CASTING

Casting is part of the finishing operations in steelmaking. The liquid steel from the melt shop is transformed into intermediate, marketable products. Casting can be done as a batch process, producing ingots or slabs; or a continuous process, producing blooms and billets. New technology is moving towards the near-net-shape casting of the products. The purpose is to achieve as close to the final product in casting as possible, without the need for

extensive secondary processing [13], [14], [17]. This reduces the consumption of energy in downstream processes.

1.4.6 SHAPING MILLS

In most cases after casting, the products are shaped further to marketable products in a series of rolling and shaping operations. The hot- and cold-rolling processes are two common processes that are discussed in this section [13], [14].

Hot-rolling

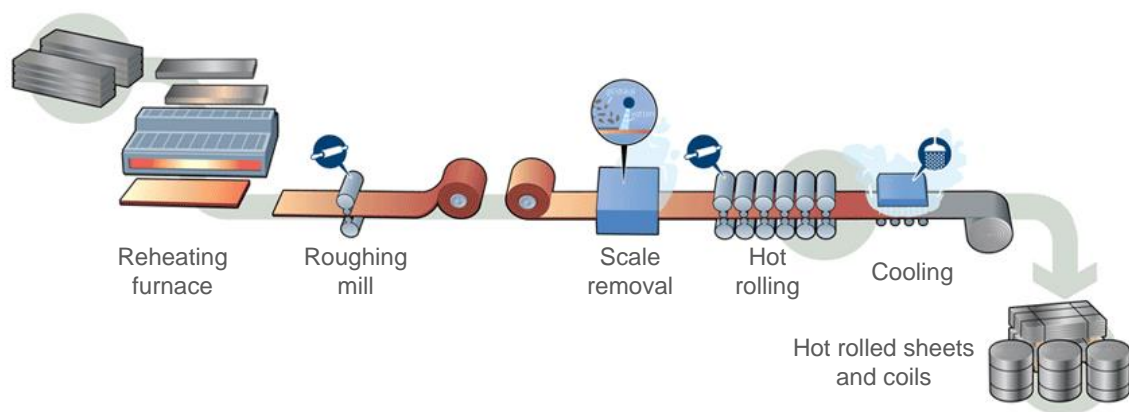


Figure 1-5: Overview of the hot rolling process, adapted from The Institute for Industrial Productivity ³

In hot-rolling steel, slabs are reduced to hot-rolled coils in a hot strip mill shown in Figure 1-5. The mill consists of a reheating furnace that heats the slabs to the required temperature for rolling using fuel gases for thermal energy. The slab is first reduced in size in a roughing mill. After this, the coil, bloom or billet is reduced further in thickness in a finishing mill. The product is then coiled or bundled for either further production in a cold-rolling mill or for sale as a final product [13], [14].

Cold-rolling

Cold mills produce sheets or plates from hot-rolled coils, produced in hot-rolling. The products can be used for a variety of purposes like automobile bodies and tin cans. The coil is cleaned of its iron oxide film in an acid bath and cold rolled. Afterwards, the product is

³ The Institute for Industrial Productivity, "Rolling Mills." [Online]. Available: <http://ietd.iipnetwork.org/content/rolling-mills>. [Accessed: 16-Apr-2018].

annealed to achieve the required malleability. The properties can be further improved with operations like pickling to achieve improved metallurgical properties [13], [14].

1.4.7 REHEATING FURNACES

Reheating furnaces are important components in hot-rolling operations and integrated steelmaking facilities in general. Reheating furnaces are used to heat the cast products to the required temperature for rolling, milling, forging or other shaping operations. The two main types of furnaces are walking beam and pusher type reheating furnaces. A section view of a walking beam type reheating furnace is shown in Figure 1-6. They operate at temperatures exceeding 1100°C [18].

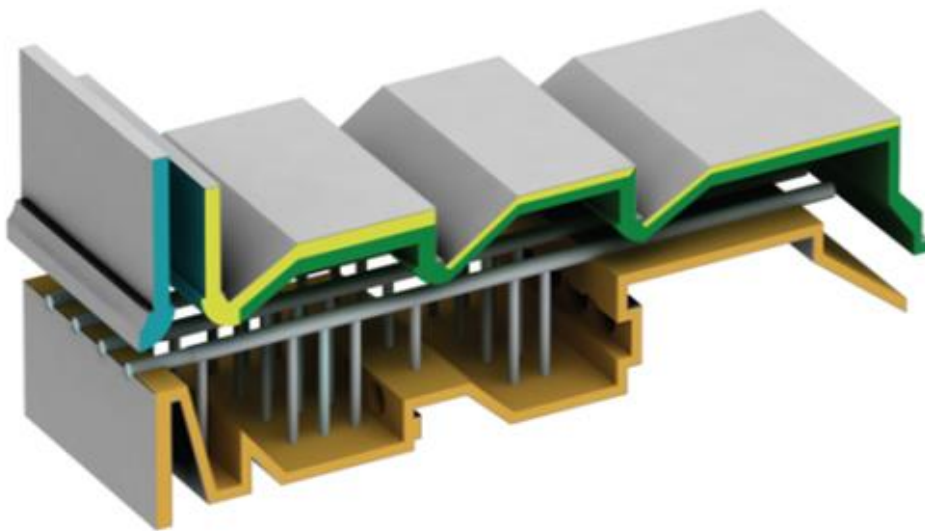


Figure 1-6: Section view of a walking beam type reheating furnace, adapted from Kyungdong Worldwide ⁴

A reheating furnace consists of different zones, usually a preheating, heating and soaking zone. The last two zones can be further split into a left and right or upper and lower zone. The products are charged at the preheating zone side of the furnace and move through the heating and soaking zone, after which they are discharged. Most heating happens in the heating zone and temperature homogeneity in the product occurs in the soaking zone [18].

These zones contain burners for heating the products with different fuel sources. The burners can operate on liquid or gaseous fuels, depending on the design and the availability of gases. The gases that can be used as energy sources are process by-product gases and

⁴ Kyungdong Worldwide, "Reheating furnace." [Online]. Available: http://www.kdw.co.kr/en/business/refractories_04.asp?tab=02. [Accessed: 16-Apr-2018].

purchased gases. These fuels have different properties and they react differently in the furnace [18]. The furnace energy efficiency changes when operating on different fuel gases. More detail on the different fuel gases is provided in the next section.

Operational issues occur frequently in reheating furnaces. The precise control of temperature in the furnace is important. As materials rolled at sub-optimum temperatures can cause operational problems, thereby increasing production costs. The loading temperatures of the stock can also vary and affect the fuel flow rates in the furnace. The production rate in a plant varies and process interruptions require intervention in furnace control operation [18]. These operational problems form part of the research motivation stated later in this chapter.

1.5 Overview of fuel gases in steel production

1.5.1 PROPERTIES OF GAS

As discussed in the process overview of steel production facilities in the previous section, there are numerous fuel gases used throughout the process. These gases are used for heating purposes throughout the works in the raw material preparation, iron making and steel making processes. They consist of hydrocarbons, hydrogen, carbon monoxide or mixtures of these gases. The gases are gaseous under normal environmental conditions and can be transported by pipelines [19].

To determine the impact of the reduction in energy and the costs thereof, the energy content must be determined. As it is not practical to measure the heat of every reaction that takes place in a plant, the heat of reactions is estimated for known components in the gases under standard conditions. These values include the standard heat of reactions and combustion. The value used for determining the heating energy of the gas is the Calorific Value (CV). The value is determined by calculating the pre-combustion temperatures before the reaction and vaporising of all vapour in the process [19].

1.5.2 PROCESS BY-PRODUCT GASES

The previous section gave an overview of the properties of fuel gases. Some of the components in the steelmaking process produce by-product gases that contain energy. These gases can be used for heating throughout the works as was discussed in the process overview. These gases can account for about 30% of the total energy consumption in the

iron and steel industry [20]. The gases are normally cleaned before being distributed throughout the plant in complex pipeline distribution networks.

Examples of by-product gases that are found in the steel industry include Blast Furnace Gas (BFG), Coke Oven Gas (COG), BOF gas and Corex gas. Tar-derived oils are also produced in some processes. Each fuel has different chemical compositions and characteristics that are used to determine the heats of reaction and the CV value of the gas as discussed in the previous section [18].

1.5.3 PURCHASED GASES

Other gases used for thermal energy in the steel industry are fuel gases that can be purchased from outside suppliers. This would be necessary if the by-product gases are not produced on the plant or the quantities available do not meet the plant's energy demands. Gases purchased incur additional operational costs as they are purchased from other business entities and not produced inside the facility. Purchased gases are a key motivation in this study that is discussed later in this chapter.

Some of the gases that are frequently purchased are natural gas and Liquid Petroleum Gas (LPG). Natural gas is a hydrocarbon gas that contains primarily methane and ethane. It typically has a CV value of 38 megajoule per cubic metre [MJ/m³]. The gas is usually purchased in gigajoule [GJ] quantities and not volume [21]. LPG is a mixture of several liquid gases including hydrocarbons, propane and butane. The gas is usually purchased and transported by freight, sea and pipelines [22], [23].

1.5.4 GAS DISTRIBUTION NETWORKS AND OPERATIONAL PROBLEMS

The gases described in the previous section are distributed throughout the works in a series of pipelines. A diagram of a typical by-product gas distribution network is shown in Figure 1-7. BFG and COG are produced by the blast furnace and coke ovens respectively. The gas is distributed to plant consumers through complex pipeline networks. The gas that is not consumed is considered surplus and are buffered in gasholders and boilers. The gasholders provide storage capacity and they stabilise the pressure in the pipelines. The boilers provide additional electrical energy to the production facility [24].

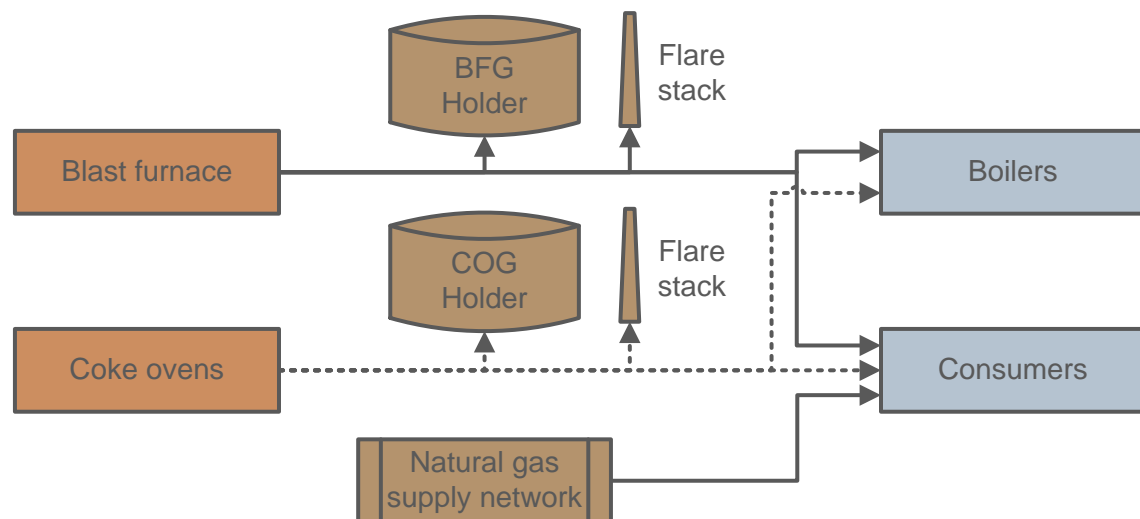


Figure 1-7: By-product and natural gas distribution network

The gasholder moves up or down to increase or decrease its capacity of by-product gas storage. The surplus gas can be consumed by the boilers for use in alternators. The control of the gas network is an integrated and complex problem. Some operational issues can occur in the plant gas distribution network. When the gasholder reaches its upper control limit, the surplus gas is flared in a flare stack. This means that the surplus gas exceeds the plant demand and energy is lost [6].

The opposite is also true for when the gasholder reaches its lower control limit. The plant's gas consumption exceeds the supply of by-product gas. If the boilers cannot reduce consumption, another issue that will occur is that the gasholder needs to be locked in place by a seal so that it is not damaged. This means that the gasholder cannot control the pressure in the system anymore and the control is performed by the flare stack. This is an extremely undesirable occurrence and it takes time to rectify the problem. Operational costs increase as the gas shortage also needs to be addressed by purchasing the gases mentioned previously to meet the plant's energy demand [6].

A human process controller or operator is responsible for controlling this complex, integrated system. The steelmaking process is a continuously variable system. It is impossible to take all parameters into consideration without the assistance of computer systems. This leads to the motivation and the objective of this study set out in the next section.

1.6 Research motivation and objective

The South African steel industry is under immense economic pressure with declining production figures, reduced steel exports and increasing steel imports. The industry needs to reduce operational costs to remain competitive in these market conditions. The steelmaking process is an energy-intensive industry with energy costs contributing to about 20% of the total operational costs of an integrated steel facility.

An integrated steel production facility is a complex process involving many components and processes. An important part of the process is the finishing milling of the final products. This process often consists of hot rolling operations where a reheating furnace is used to heat stock for rolling. A reheating furnace consumes about 70% of the total energy of the finishing process. The temperature control of these furnaces is an important factor achieved by changing the flow of fuel gas to the furnace. In some plants, the furnace can switch operation between different fuel gases, like natural gas and process by-product gases.

By-product gases are supplied through a distribution network by processes upstream of the reheating furnaces. By-product gas shortages in steel plant gas distribution networks are mitigated by purchasing natural gas or other fuel sources from outside suppliers. A human operator is responsible for deciding where to recoup the by-product gas shortage from. The reheating furnaces are a logical choice as they can be switched to other fuels relatively quickly. Different reheating furnaces have different operational efficiencies on different fuel sources. The operator cannot optimally redistribute the available by-product gas. The optimal redistribution of by-product gas results in minimal natural gas purchases and reduced operational costs for the plant.

The objective of this study is to develop a methodology that can be used in an integrated steelmaking facility to reduce operational costs in steel production mills. The method must improve the decision-making process for selecting gas consumers, specifically reheating furnaces, in a gas distribution network. It should assist a human operator with controlling the gas distribution network in the most energy-efficient way possible with the objective of improving energy cost performance of the facility. These objectives of this study are achieved by way of novel contributions that are set out in the following section.

1.7 Novel contributions of the study

1.7.1 NOVEL CONTRIBUTION 1

A novel energy characterisation model for mill reheating furnaces.

Motivation for the research contribution:

The problem is that the efficiency of a reheating furnace changes when operating on different gas mixtures and varying production loads. The energy consumption efficiency of a reheating furnace needs to be modelled and simulated to assist with this.

Limitations of existing research:

A detail review on the limitations of energy modelling and simulation research is conducted in Section 2.2. Benchmarking of energy consumption and intensity modelling use predominantly energy per tonne models for comparisons. These models do not allow for variation in production rate and are not developed for different gas mixture ratios.

Software tools require complex measurements like the geometry of the furnace. They only provide static feedback that can be used to make design changes to the furnace. Adding on to this are Computational Fluid Dynamics (CFD) models, which require long computation times and do not allow for frequent changes of input parameters like fuel gas mixtures.

The simulation models found in literature all require detailed information to simulate furnace parameters at varying production rates. However, these parameters focus on furnace schedules and temperature setpoint modelling and not energy consumption.

Research question:

Can a simplified furnace energy characterisation model simulate energy consumption at various production rates and gas mixture ratios?

The contribution of this study:

A new simplified energy characterisation model for reheating furnaces was developed. The model can map and simulate the furnace energy consumption for different gas operation mixtures under varying furnace production loads. The model achieves this with limited input measurements and information.

1.7.2 NOVEL CONTRIBUTION 2

A new optimisation model of different gases in a gas distribution network.

Motivation for the research contribution:

The problem is that the gas distribution network cannot be optimised based on the energy efficiency characteristics of each of the furnaces. An integrated network of the furnace energy characterisation models is required to optimise the by-product gas distribution.

Limitations of existing research:

A detail review on the limitations of research on reheating furnace and gas network optimisation is conducted in Section 2.3. Optimisation models that are available for the efficiency of an entire steel facility aim to improve different aspects of the plant. Some look mainly at the complete utilisation of the available thermal energy and suggest high capital expenditure improvements to the plant. Others look to improve the flow of product to the same effect. Other studies recommend improved process control for a major impact on energy efficiency.

Most optimisation models focus on the improvement of temperature control in a furnace. Other models focus on the increase of electricity generation and the improved control of boilers and gasholders. These studies do not focus on the effect of changing fuel sources in the furnace. Models are either limited to low variability in production rates or require complex measurements from the furnace to implement. All the models are implemented or analysed on a single furnace and do not consider the effect of other furnaces' efficiencies. They do not optimise the gas consumption network as an integrated system.

Research question:

Can a characterised optimisation model simulate the gas distribution of multiple furnaces for the optimal cost?

The contribution of this study:

An optimisation algorithm was developed that uses an integrated network of the new furnace energy characterisation models. The model works with limited information from the furnaces and can optimise the gas distribution of the network for a single point in time for any operational configuration.

1.7.3 NOVEL CONTRIBUTION 3

A real-time optimisation system for gas distribution optimisation.

Motivation for the research contribution:

The problem is that the operator cannot optimise the gas distribution network based on all the efficiency characteristics of the furnaces in real-time. The development of a real-time gas network optimisation model for reheating furnace gas distribution is required.

Limitations of existing research:

A detail review of the limitations of research on real-time optimisation systems is conducted in Section 2.4. Production scheduling systems do not simulate the effect of energy consumption of the components. They rely on production scheduling or buffers to shift load to other time periods for energy cost improvements. The systems that do operate in a network, do not consider the effect of other components' effect on the network energy efficiency. They also cannot simulate the effect of changes to the system.

Model predictive control systems require complex measurements from the reheating furnace to operate. In multiple cases, they are suitable for real-time use. They focus on the prediction and improvement of the temperature setpoints and not the effect of energy efficiency. These systems work on a furnace as a single entity and do not work as an integrated network of furnaces for improved control of the gas distribution network.

Research question:

Are real-time gas network distribution optimisation systems available and practical to implement?

The contribution of this study:

A real-time optimisation system of a gas distribution network was developed for steel plant reheating furnaces. The system simulates and optimises the gas network for reduced natural gas consumption using the new optimisation algorithm in real-time. A user interface provides an operator with the required action and can also predict what the effect of changes to the system will be.

1.7.4 PUBLICATIONS RESULTING FROM THE STUDY

Published work

S. G. J. Van Niekerk, H. G. Brand, and C. J. R. Kriel, “Practical and verifiable quantification of energy consumption in large industries for energy reporting and incentive applications,” in *Industrial & Commercial Use of Energy (ICUE)*, 2016, pp. 199–205.

S. G. J. Van Niekerk, W. J. J. Breytenbach, and J. H. Marais, “Developing an optimisation model for industrial furnace gaseous fuel distribution for energy cost savings,” in *Industrial & Commercial Use of Energy (ICUE)*, 2017, pp. 38-41.

Publications in progress

S. G. J. Van Niekerk, W. J. J. Breytenbach, and J. H. Marais, “A real-time optimisation system for reheating furnace fuel gas distribution,” for *Industrial & Commercial Use of Energy (ICUE)*, 2018.

1.8 Overview of thesis

Chapter 1

An overview of the challenges in the iron and steel industry is provided. Background on integrated steelmaking facilities and their energy consumption is discussed. The motivation and objective of the study are provided. Finally, the novel contributions of this research are summarised.

Chapter 2

A literature review is conducted on topics related to energy modelling of reheating furnaces, optimisation of their energy consumption and real-time energy optimisation systems.

Chapter 3

A research methodology is developed to model the energy consumption of a reheating furnace. These models are then integrated into a network and the energy distribution is optimised for reduced cost. Finally, a system is developed for real-time optimisation.

Chapter 4

The methodology is validated on a steel production facility in South Africa. The results are verified, analysed and validated in this case study.

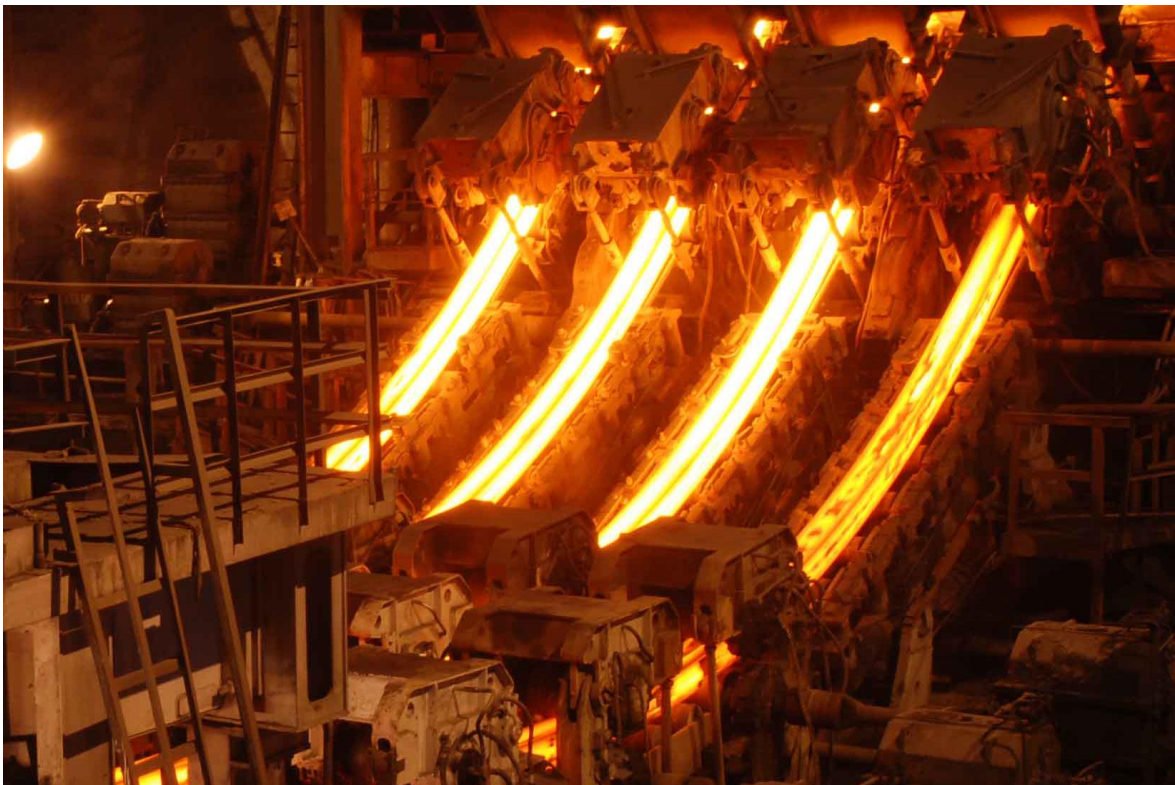
Chapter 5

The chapter provides an overview of the work completed and final discussion of the study. Recommendations for further study in energy cost performance are provided.

1.9 Summary

In this chapter an overview of the challenges faced in the iron and steel industry was provided. Background on integrated steelmaking facilities and their energy consumption was discussed. The motivation and objective of the study were provided. Finally, the novel contributions of this research were summarised. The next chapter conducts a detailed literature review on the current research and work available.

2 LITERATURE REVIEW



Continuous casters. ⁵

⁵ Vizag steel, *Steel Melt Shop & Continuous Casting*, 2015 [Online]. Available: <https://www.vizagsteel.com/code/Infrastr/sms.asp#thumb>. [Accessed: 30-Sep-2015].

2.1 Preamble

The motivation and research objective have been derived from the background in Chapter 1. The background was provided on steelmaking facilities with the focus being placed on reheating furnaces and the supply of fuel gas to these plants. The fuel gas distribution network is controlled by an operator. The network and reheating furnace characteristics are too complex to operate at optimum efficiency in real-time.

This chapter consists of a literature review of current research and work. The topics covered are energy modelling of reheating furnaces, optimisation of reheating furnaces and real-time optimisation systems. These topics are subdivided further in each relevant section. The layout of the literature review described can be seen in Figure 2-1 below.

The novel contributions of this study are highlighted in each section of the literature review conducted. This is done in a discussion of the limitations of current research and how it relates to the research motivation and objective. The limitations are used to derive three research questions that need to be addressed by the work in this study.

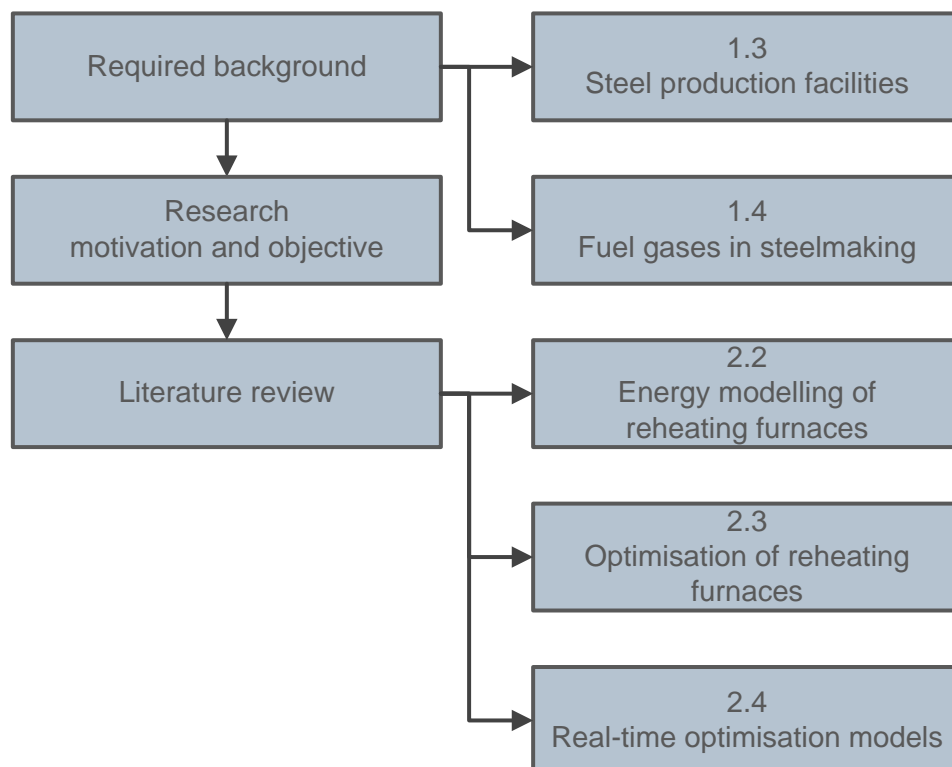


Figure 2-1: Literature review overview

2.2 Energy modelling of reheating furnaces

2.2.1 HIGHLIGHTS OF THIS SECTION

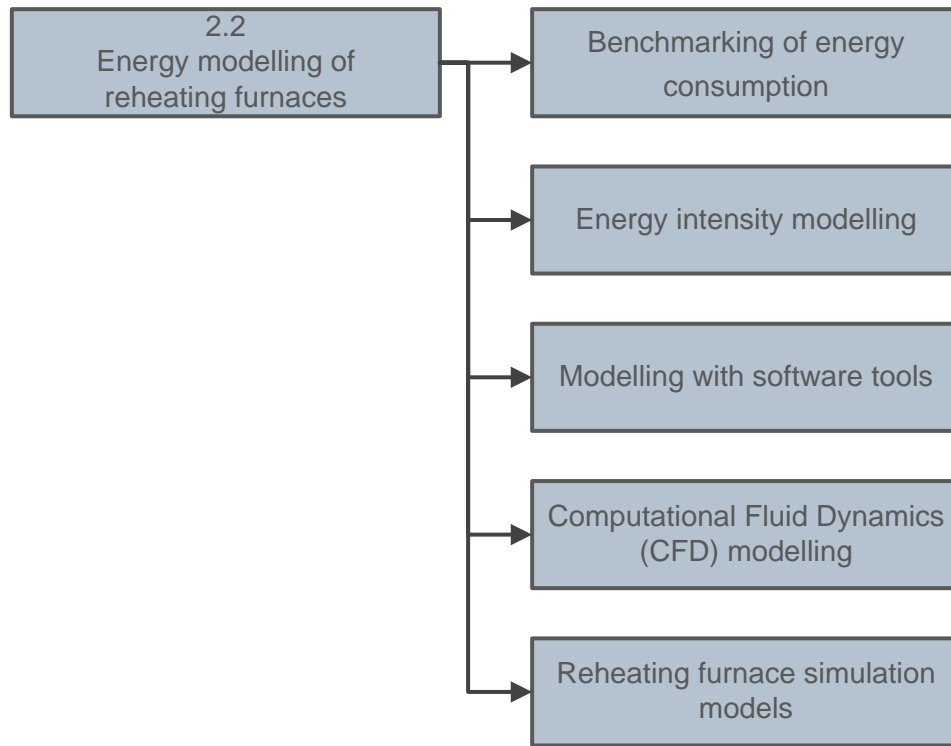


Figure 2-2: Overview of research on reheating furnace energy modelling

To better understand the effect of changing fuels in reheating furnaces, energy characteristic models are required. These models must be able to simulate the energy consumption of the furnace at varying production rates and fuel supply mixtures. An overview of the different energy models of reheating furnaces discussed is shown in Figure 2-2. The subjects that are discussed in this section are:

- An overview of steelmaking benchmarking is provided;
- Energy intensity models and studies are reviewed;
- Modelling tools that have been used on reheating furnaces are discussed;
- A review of Computational Fluid Dynamics (CFD) models is done; and
- Simulation models for reheating furnaces are reviewed.

2.2.2 BENCHMARKING OF ENERGY CONSUMPTION

One of the simplest forms of energy modelling found in the steel industry is benchmarking of energy consumption. The iron and steel industry has been benchmarked according to the best practice energy intensity values per technology. The term “world best practise” refers to the most energy efficient technologies that are in commercial use [25].

The values are modelled as an energy intensity value expressed as energy consumption per physical production unit. The most common of this is a gigajoule per tonne [GJ/t] allocation [25]. The energy intensity values for different countries can be compared using this metric. These values are used for comparison purposes; however, they do not provide much insight into the plant.

2.2.3 ENERGY INTENSITY MODELLING

Preamble

Following on the energy benchmarking consumption models, is the application of energy intensity modelling in steel plants and reheating furnaces. This section reviews the research found on energy intensity modelling in the steel industry.

An energy apportionment model for a reheating furnace in a hot rolling mill

Lu et al. developed an energy apportionment model for use with different types of steel billets in a walking beam reheating furnace. The model is divided into time segments that span from billet loading time to unloading time. Energy is then allocated to every segment. Results show that energy allocation has significant implications for the formation of the billet loading order planning, production rhythm and energy assessment. All these factors need to be taken into account in order to achieve an energy efficient operation [12].

The study found that the size of the billets has an impact on the energy consumption of the furnace due to change in production rhythm. The energy allocation also changes with differing steel grades. It was found that providing a reasonable loading schedule based on billet size and steel grade will improve heating and provide energy savings. The model highlights that proper maintenance management is important to achieve a normal production rhythm and decrease the energy allocation [12].

The study modelled the furnace energy consumption based on GJ/t allocation separated by time of the billets in the furnace. The results were analysed for different steel grades and billet sizes loaded into the furnace. The study focused on production planning and not on the effect of different fuels on the efficiency of the reheating furnaces. The study required detail production records from the plant.

Energy and material flow models for the U.S. steel industry

Andersen et al. developed calibrated energy and material consumption models for the U.S. steel industry. They investigated energy end-use models, material and energy flow process models. Models were developed for the energy intensity of every step in the steelmaking process. These models can be used for benchmarking as well as a baseline for the assessment of the implementation of new technologies in the process [26].

The study provides a simplified solution to the complex process of steelmaking. It does not, however, consider variation in production. The models only provide an energy intensity comparison which works well for linear comparisons. What is required are energy models that can simulate a reheating furnace under varying production loads and operating on different gas mixtures. The models in the study are too high level for application in this study.

Comparison of iron and steel production energy use and energy intensity in China and the U.S.

Hasanbeigi et al. set out to compare the energy intensities of the U.S and China. They developed a methodology that can be used for this purpose. They found that the process configuration of the two countries are very different if the use of Electric Arc Furnaces (EAF) is considered. The model developed considers numerous process variables to determine the energy intensity of the processes in steelmaking. Using the model a much more accurate comparison of technologies is the results [27].

The models can be used to compare different countries' energy intensities. The models do not, however, simulate the actual energy consumption of the components. They also do not consider the effect of fuel switching as in normal operation.

The quality of energy intensity indicators for international comparison in the iron and steel industry

Farla et al. highlighted the importance of energy intensity comparisons of different countries' steelmaking industries in national policymaking. They found that production data availability and accuracy is good for the use of energy intensity calculations. However, the uniformity of different international publishers of energy data for different countries varies. This makes a reliable comparison of international energy intensity difficult [15].

The model used for the comparison is a process flow and energy intensity calculation. It is a simplified solution for modelling but it is not adaptable for changing fuel mixtures and production rates. More adaptable and detailed models are required for this study.

The energy consumption and carbon emission of the integrated steel mill with oxygen blast furnace

Jin et al. analysed the potential for CO₂ emission reduction with the new process of an oxygen blast furnace with top gas recycling compared to the conventional integrated iron-making process. To complete the comparison a material and energy flow model of the furnace was developed. The model indicated a significant reduction in CO₂ emissions compared to the conventional route [28].

The model establishes the parameters of the material and energy flows of the blast furnace. This is based on mass and energy balances of the two processes. This is a comprehensive model and not a simplified solution. It points out the differences between two technologies. The model requires detail design information of the furnace. Its use in the simulation of fuel switching in reheating furnaces is limited.

Performance assessment of a steel reheating furnace

Myalapalli assessed the performance of a reheating furnace that was operating at a reduced production output compared to its design specifications. A heat balance was performed to assess the deterioration in production. Several adjustments that can be made to a furnace to increase its efficiency were proposed. The efficiency losses in the furnace were modelled as an energy flow rate of energy per hour. By using the models, adjustments were made to the furnace control and considerable energy savings were achieved [29].

The model used does not require complex measurements of all the furnace parameters. A relatively short time period of ten days was used to model the furnace operation. The model also cannot simulate furnace energy consumption. The furnace also operated on one gas mixture.

Summary of energy intensity models

The energy intensity models reviewed in this section are mainly used for comparison purposes. Be it comparison between different countries or the impact of the implementation of new technologies. These models are not flexible in nature and do not allow for changes in production loads, as well as the dynamic changing of fuel gas supplies. More detail from the output of the models is required in terms of energy at changing loads and fuel sources.

2.2.4 MODELLING WITH SOFTWARE TOOLS

Preamble

Another option in energy modelling is the use of existing software application tools to simulate the energy consumption of the reheating furnaces. In this section the software tools found in literature and industry are reviewed. Their applications and relevance to this study are discussed.

Energy efficiency assessment by process heating assessment and survey tool (PHAST) and feasibility analysis of waste heat recovery in the reheat furnace at a steel company

Si et al. apply the PHAST tool to determine the overall efficiency and losses that occur in a reheating furnace. They found that flue gas losses have the biggest impact on energy efficiency. They recommended capital expenditure improvements with feasible payback periods to increase the efficiency of the furnace [30].

Of note for application in this study is the method followed for the capturing of data for the survey tool. They took detailed interval measurements of the furnace temperatures and gas flows at a constant production rate. This is a useful procedure for a verification process. However, this tool only provides detail on the overall losses of the reheating furnaces and not the effect of fuel switching or variation in production loads.

Strategic analysis of energy efficiency projects: a case study of a steel mill in Manitoba

Thompson et al. performed analysis on energy efficiency initiatives on a steel mill to determine the feasibility of the opportunities. To achieve this, they used two modelling tools: the PHAST tool and the RETScreen Clean Energy Project Analysis Software. The software indicated a few initiatives that had short payback periods [31].

The study shows that it is useful to use modelling of systems to base decisions on. The software used is useful for determining what the effect of changes to the design of a system would be, but for this study, it cannot achieve the requirements for the simulation of a furnace's energy consumption with varying loads and fuel sources.

A bottom-up analysis of China's iron and steel industrial energy consumption and CO₂ emissions

Chen et al. analysed the future steel demand, scrap consumption and energy consumption in China. They used a systems dynamic model and a bottom-up energy system model to simulate the future steel demand of various sectors. They also predicted the influence of the increased deployment of energy efficient technologies in the iron and steel industry [32].

They modelled the CO₂ and energy intensity of the sector. A consideration that can be taken from the study is that changes in the process influence future operation. The application of this model is for prediction of market conditions and not on energy efficient control of reheating furnaces.

Numerical modelling of a walking beam type slab reheating furnace

Hsieh et al. completed the three-dimensional modelling of the radiative heat transfer and turbulent reactive flow of a walking beam type slab reheating furnace. They used commercial software, STAR-CD, to model the reheating furnace. The software considers all the geometrical aspects of the furnace. They found that the furnace heating efficiencies could be modelled with reasonable accuracy [33].

This type of model can be used for determining the impact of configuration changes to the furnace. The model requires detailed measurements from the furnace, it also assumes a constant product feed rate. The study is useful if capital is available to change the design

of the reheating furnace. What is required in this study is a model that can simulate real-time changes in a furnace.

Summary of modelling with software tools

Some software application tools exist that can assist the user with modelling a reheating furnace. These software tools are mainly used for modelling the furnace characteristics as an energy balance to indicate thermal losses. They are useful for evaluating the design of a furnace and for decision making on changing characteristics, upgrading or maintain reheating furnaces. What is required is a model that can simulate the furnace energy consumption in real-time for different operational loads and different configurations of fuel gas supply to the furnace.

2.2.5 COMPUTATIONAL FLUID DYNAMICS MODELLING

Preamble

Another method frequently used for modelling reheating furnaces are Computational Fluid Dynamics (CFD) models. These models simulate the reheating furnace using first principles and the actual geometry of the furnace. This section reviews the available CFD models found in literature and their application to this study.

A new methodology for Computational Fluid Dynamics three-dimensional simulation of a walking beam type reheating furnace in a steady-state

Casal et al. presented a new simulation model of a reheating furnace that converts the furnace operation into a steady-state problem. The reduction of the system to steady-state significantly reduces computational time compared to transient models. The model calculates important furnace variables like the temperatures of the billets, exhaust gas temperatures in the different zones and the heat absorption of the billets. This model can be used to predict the effect of changes to the furnace [34].

The simulation model presented in the study requires numerous inputs to simulate the furnace. This model provides excellent information for changing the furnace characteristics. It allows for complex decision making based on all the information. The solution of the model is, however, not simplified. The model was also tested on natural gas only and the production rate was not varied since it was not within the scope of the study.

Modelling of the slab heating process in a walking beam reheating furnace for process optimisation

Tang et al. created a new methodology for reducing the results of a three-dimensional CFD analysis to a two-dimensional solution of a walking beam reheating furnace. They can simulate the flow and heat transfer characteristics of the furnace. The two-dimensional heat transfer model can be used to simulate conditions in the furnace. They state that the system can be used by engineers to troubleshoot and optimise the furnace [35].

The study provides a comprehensive overview of a furnace's operation. The model requires many variables for computation of the outputs. If the system were to compute the effect of the changing of fuel gas, a detailed chemical analysis of the gas would be required. The system provides good detailed information, but the model is not simplified.

Zone modelling of the thermal performances of a large-scale bloom reheating furnace

Tan et al. investigated the feasibility of using two- and three-dimensional CFD models to predict the thermal performance of a bloom reheating furnace. They found that no significant difference occurred between the results of the two models. They simulated the effect of a reduction in production throughput on the temperature of the furnace. They found that the furnace response to production changes is not unique. They suggested that an interpolated library could be used in operation of the model without rerunning the CFD model [36]. The shortfall of a CFD analysis model is present in the study, being long computational times and the requirement of detailed furnace data. This is not a simplified solution.

CFD analysis of a pusher type reheating furnace and the billet heating characteristic

Mayr et al. developed a new method for simulating a reheating furnace in steady-state. This model was developed for a pusher type reheating furnace. The billets are side by side in this type of furnace and were modelled as a viscous fluid. The result is a reduced computational time compared to a CFD analysis. They achieved good results compared to an iterative approach as well [37].

The main purpose of the study is to reduce the computational time of a CFD analysis. It is only possible to use this approach in a pusher type reheating furnace. The model can be used to simulate furnace characteristics for changing furnace geometry without tests. The study requires complex measurements. The production rate is also taken as a constant value.

Experiment research and simulation analysis of regenerative oxygen-enriched combustion technology

Guo et al. analysed the combustion modes with the combination of regenerative and oxygen-enriched combustion technology. They modified a CFD simulation to simulate the operating conditions. They found that energy savings were achieved while temperatures in the furnace increased [38]. The use of CFD analyses requires detailed data from the furnace and long computational times, it is not a simplified solution. The use of this technology requires capital expenditure to implement.

Summary of CFD models

CFD models are complex in nature. Their shortfall in their application in this study is that they require detailed measurements from the furnace as well as the geometrical measurements of the furnace. They are typically not adjustable since they require long computational times to solve. They do not allow for variation in production rates and mainly provide a static solution for use in furnace design and operational changes. What is required for this study is a model that can simulate the effect of changes in the fuel supply in dynamic plant operation under different furnace loads.

2.2.6 REHEATING FURNACE SIMULATION MODELS

Preamble

The final part of this section is simulation models found in literature. These models simulate various aspects of a reheating furnace. In this section a review is conducted of the available research on reheating furnace simulation models.

A comparative study on special and non-special reheating furnace modes based on simulation technology

Lu et al. analysed the production scheduling of a slab reheating furnace. They developed a scheduling model for the furnace. The model considered the idling time of the furnace and the waiting time before slab charging. The model then simulated the scheduling of many steel varieties in small quantities and few steel varieties in large quantities, what they called special and non-special furnace modes. They found that they could significantly improve the thermal efficiency of the furnace [39]. The model only considered production scheduling and not the simulation of furnace energy requirements. The model requires detailed production schedules and measurements.

Modelling and experimental model validation for a pusher type reheating furnace

Wild et al. developed a mathematical model for a pusher type reheating furnace. They used first principles to develop a model of the furnace by simulating the number of slabs moving through the furnace as a discontinuous process. They validated the prediction of temperatures and exhaust gas composition against experimental measurements with good results [40]. The model reacts well to changes in production. This model requires detailed furnace production, temperature and gas composition measurements. It is not a simplified solution.

System modelling and temperature control of reheating furnace walking hearth type in the setup process

Pongam et al. set out to improve the control system of an old walking hearth reheating furnace. The furnace should control each of its zones separately. They investigated the mathematical model from experimental data. They state that the results can be used to design a controller for the reheating furnace. They achieved a significant reduction in fuel consumption in experimental results [41]. The model is a detailed control method for a reheating furnace which requires an upgrade. The system is needed to control the temperature setpoints of the furnace. It is not a simplified solution.

An online simulation model of the slab reheating process in a pusher type furnace

Jaklic et al. developed an online simulation of a pusher type reheating furnace. The model connects directly to the furnaces' information system. The model considers the furnace geometry and the slabs inside the furnace. They calculated various heat exchanges and the conduction of the slabs to simulate temperatures. They developed a Graphical User Interface (GUI) for use by the operator [42].

The model is used to calculate slab temperature in the furnace. It can vary according to production rate. The model does not perform any optimisation or provide prompts to the operator for required changes to the furnace output. Furthermore, the model requires detail measurements to simulate.

Summary of reheating furnace simulation models

Various simulation models of reheating furnaces were found in literature and reviewed. These models focus on the simulation of production schedules and the simulation of the temperature profiles of the product moving through the furnace. They require complex measurements from the furnace as well as detail production schedules to simulate. What is required to solve the problem statement of this study is a simulation model that can model the effect of changes to the furnace fuel gas supply type in real-time under different production loads.

2.2.7 SUMMARY OF RESEARCH FINDINGS

There were limitations found in existing research. Benchmarking of energy consumption and energy intensity modelling use predominantly energy per tonne models for comparisons. These models are too simple to allow for variation in production rate and are not developed for different gas mixture ratios. They can also not simulate energy on a frequent basis.

Software tools that are available require complex measurements like the geometry for the furnace. They provide static feedback that can be used to make design changes to the furnace. Adding on to this are CFD models, these systems require complex measurements and long computation times. This means that they do not allow for frequent changes of input parameters like fuel gas mixtures. They are not simple furnace models.

The simulation models found in literature all require detailed information to simulate furnace parameters at varying production rates. However, these parameters focus on furnace schedules and temperature setpoint modelling and not energy consumption.

The problem is that a human operator cannot determine the efficiency of a reheating furnace on different gases while operating the gas distribution network. The energy consumption efficiency of a reheating furnace needs to be modelled and simulated to assist with this. An energy characterisation model that can achieve this has the following requirements:

- It must map the complete furnace operational spectrum;
- Can simulate the furnace energy consumption;
- Must adapt to varying furnace production rates and loads;
- Allow for variation in gas mixture ratios of different fuels; and
- Provide a simplified solution.

The research question that arises from this section of the literature review on modelling of reheating furnaces is:

Can a simplified furnace energy characterisation model simulate energy consumption at various production rates and gas mixture ratios?

The contribution of this study that was developed in Section 3.2 of the methodology to address these shortcomings is:

A novel energy characterisation model for mill reheating furnaces.

2.3 Optimisation of reheating furnaces

2.3.1 HIGHLIGHTS OF THIS SECTION

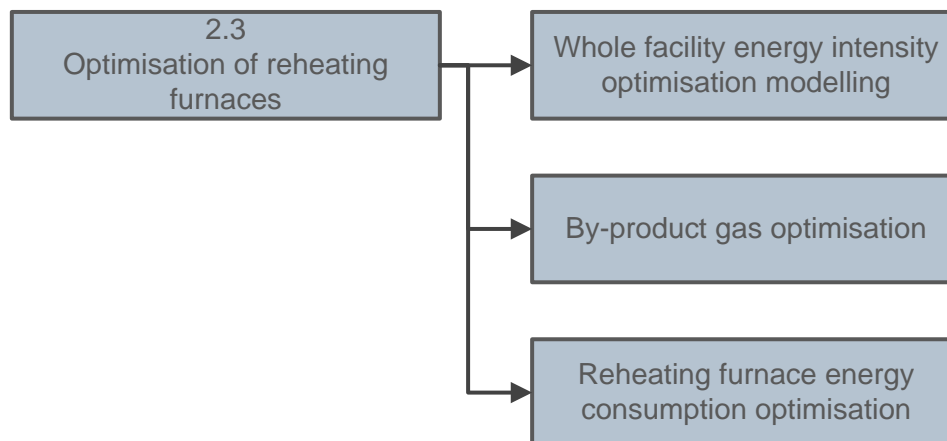


Figure 2-3: Overview of research on whole facility and reheating furnace optimisation

The modelling of the reheating furnaces in the previous section provided more detail on previous research into the effect of changing fuels and production loads on the energy consumption of the furnaces. To improve the efficiency of gas distribution based on the energy efficiency of the reheating furnaces in a network, optimisation is required. The optimisation processes and models reviewed in this section are indicated in Figure 2-3. Energy intensity optimisation and scheduling models in the steel industry are reviewed. By-product gas optimisation models and methods are reviewed. Additionally, optimisation models and control methods that were developed for reheating furnaces are reviewed.

2.3.2 WHOLE FACILITY ENERGY INTENSITY OPTIMISATION

Preamble

The first group of optimisation models that are reviewed are whole facility optimisation models. These models approach the optimisation problem from a plant based perspective. This section covers these whole facility energy intensity models in a literature review.

An energy intensity optimisation model for a production system in the iron and steel industry

Lu et al. developed an energy intensity production optimisation model for the iron and steel industry. The model analyses the ferrite flow characteristics throughout the production process. They analysed different optimisation schemes and found that the ironmaking stage shows the largest opportunity for production optimisation. They found that steel-rolling is constrained by its production path [43]. The study optimises the energy intensity based on ferrite grade. However, it does not focus on reheating furnaces or gas consumption.

An energy saving study on a large steel plant by total site based pinch technology

Matsuda et al. used a total site approach on a large-scale plant. They found that there was still significant energy savings opportunity on the plant that was thought to be energy efficient. They tracked the thermal energy consumption throughout the plant and found that lower temperatures under 300°C were not well utilised. Significant opportunity existed for increased power generation by utilising unused thermal energy [44]. The study only focused on the complete utilisation of thermal energy and not on gas consumption optimisation. The findings require large capital expenditure to implement.

Thermodynamic optimisation opportunities for the recovery and utilisation of residual energy and heat in China's iron and steel industry: A case study

Chen et al. analysed the material and energy flows in the steel industry worldwide. They state that residual heat recovery in any form plays an important role in energy efficient operations. They found that China lags behind other countries in this area. Significant energy saving and CO₂ emission reduction opportunity exists [45]. The study only seeks to reduce the lost thermal energy in the steelmaking process. This study requires an optimisation model that can redistribute the by-product gas in a gas network.

Energy efficiency improvement and cost saving opportunities for the U.S. iron and steel industry

Worrell et al. compiled a report on energy efficiency improvement opportunities in the iron and steel industry. They cite the need to reduce energy costs to increase producer earnings. They discuss energy efficient practices and technologies. Many of these initiatives have details regarding energy savings potential and payback period. This guide is intended for plant managers to review and reduce their carbon emissions in a cost-effective manner [13].

The sections of this report that pertain to reheating furnace energy efficiency are control system improvements and optimisation. They cite model-based control, artificial intelligence systems and algorithm based optimisation procedures as potential improvements [13]. Optimisation systems must be specific to what area it aims to improve in the systems. Examples are production, energy consumption, carbon emissions, process stability etc.

Energy use of reheating furnaces depend on production, operational and design factors. Significant energy savings can be achieved by upgrading the furnace. Improved process control can also increase production and have an indirect effect on energy consumption. Proper temperature control may reduce the energy consumption of the furnace [13]. These factors can be taken into consideration in the development of a solution for the problem statement of this study.

Optimal scheduling of a by-product gas system in a steel plant considering time-of-use electricity pricing

Zhao et al. developed a by-product gas scheduling model for the optimisation of peak electricity costs. The model balances two opposing objectives: the stability of the gasholder in a distribution network compared to the high costs of electricity in peak times. They could shift load to the boilers in peak times using the gasholder to achieve this. Significant electricity cost savings could be achieved [46]. The study focuses on the optimisation of the gas network with the objective of electricity cost reduction. It proves that the gas distribution network can be optimised. The model does, however, require complex information from the gas network and the boilers. It is not a simplified solution to the problem being optimised.

A review of the optimal scheduling of by-product gases in steel making industry

Zhao et al. also completed a review of the current methods for the scheduling of by-product gases in steelmaking facilities. A consideration from the study is that the boiler efficiency is

affected by load and previous studies set this as a constant value [47]. A part load ratio was calculated for the boiler based on the actual operation. They focused on the achievement of an optimal schedule for by-product gas and not the optimisation of gas distribution. They found that a key challenge is finding the balance between accuracy and solving speed of the scheduling model.

Summary of whole facility optimisation models

Whole facility optimisation models were reviewed in this section. Shortcomings in the research conducted were found with regards to the problem statement of this study. Some studies focussed on the complete utilisation of thermal energy throughout the plant. Other studies looked to optimise the flow of material and throughout the works. Finally, some studies modelled the optimisation of the plant schedules for improved electricity generation and reduced costs. These models require numerous measurements throughout the works since they focus on the whole facility. These studies do not focus on reheating furnaces and their energy efficiency or the optimisation of gas distribution to the furnaces.

2.3.3 BY-PRODUCT GAS OPTIMISATION

Preamble

This study requires the optimisation of the by-product gas and purchased gas distribution to the furnaces. This section reviews research found on by-product gas optimisation models. The optimisation models utilise linear programming algorithms to perform the optimisation.

An improved plant-wide multiperiod optimisation model of a by-product gas supply system in the iron and steelmaking process

De Oliveira Junior et al. improved an existing mixed integer linear programming (MILP) model to solve the problem of by-product fuel distribution. The goal of the model is to maximise energy utilisation in the plant boilers. The objective function, which defines the problem, is modified with penalties to improve the operational performance of the model. The weights are determined using the maximum operational characteristics of the boiler burners and the gasholders. They found that they could increase electricity generation by controlling the gasholder at a lower mean value [48].

What can be considered from the study is that the burners were characterised by maximum fuel flow for use in the model. The limitations are that the proposed model focuses on maximising electricity generation in the plant generators and the control of the gasholder. It was not implemented on the plant reheating furnaces. The model uses detail measurements from the different components to optimise the decision making in gas distribution based on the calculated penalties.

A mixed integer programming model for the gas distribution problem with complex gas applied characteristics

Sun et al. put forth a MILP mathematical model to solve the problem of gas distribution in steelmaking. The model is built on actual data from a steel plant, constrained and defined with variables from the plant's demand, gasholder levels and boilers. They used available software tools to solve the model. They recommended the development of an optimisation model due to the cost and limitations in the adjustment of the software utilised. They found that smaller fluctuations in the gasholder had minimised cost results [49].

The study focusses on the optimisation of the boiler energy consumption and the control of the gasholder levels. The goal was to stabilise fluctuations in the gasholder and increase electricity generation. The model requires complex measurements from the plant to optimise. The study does not focus on the optimisation of furnace gas consumption.

A novel multiperiod mixed integer linear optimisation model for the optimal distribution of by-product gases, steam and power in an iron and steel plant

Zeng et al. developed a MILP model for the optimisation of the gas distribution in a steelmaking facility. The model focuses on the optimisation of gases, steam and power. They use variables that model the fuel selection, gasholder level, ramp rate, constant generation rates of by-product gas, constant demand profiles of by-product gases, steam and electricity generation. They state that the optimal distribution of by-product gases is complex due to the multitude of available combinations [50].

The study focuses on the optimal distribution of by-product gases to the boilers, specifically to the burners, turbines and waste heat recovery components. The MILP model requires a multitude of measurements from the plant to optimise. The study does not focus on the optimisation of fuel distribution to the reheating furnaces or other components in the plant.

Optimal allocation of surplus gas and suitable capacity for buffer users in a steel plant

Yang et al. developed a linear programming model for the optimal allocation of by-product gas in a steelmaking facility. The model optimises the distribution of by-product gas using the plant capacity buffers. The model indicated an increase in boiler efficiency and a surplus gas related generation increase [24]. New capacities for the gasholders and boilers and the construction cost curve thereof are proposed. The study focuses on the improved control and design of the plant's boilers and gasholders. The efficiency and gas consumption of reheating furnaces are not considered. The study also does not look at the optimal distribution of gas with the focus on decreasing purchased gas consumption.

A mixed integer linear programming model concerning the optimisation of penalty factors for the short-term distribution of by-product gases produced in the iron and steelmaking process

Zhao et al. developed a MILP optimisation model for the optimisation of the by-product gas distribution in a steel plant. The model optimises the control of the boilers and gasholders in the distribution network. The model focuses on the allocation of penalty factors to the linear programming model. These penalty factors include deviation of the gasholder level and the time it takes to switch fuels in the boilers [51]. They found that the penalty factors significantly influence the output of the optimisation model. They found that the use of the model compared to manual operation decreases the fluctuation of the gasholder level and the boiler loads.

The limitations of the study, regarding this study, are that the model only looks at the optimisation of the control of the gasholders and not the boilers. The efficiency of the components in the network, like reheating furnaces, are not considered. The components are only modelled as consumers. What can be considered from the study is the effect of switching burners to other fuels in the boilers.

Summary of by-product gas optimisation models

This section reviewed the by-product gas optimisation models found in literature. The majority of these models use MILP optimisation models for the optimisation of by-product gas. The limitations of this type of model are that they require detailed information from the facilities. They focus on the optimisation of the control of the gasholders and the boilers to reduce fluctuation and increase electricity generation. However, these optimisation models

do not focus on the optimisation of by-product gas to the reheating furnaces and the effect of their energy efficiency on the network energy distribution.

2.3.4 REHEATING FURNACE ENERGY CONSUMPTION OPTIMISATION

Preamble

The optimisation of reheating furnaces is a core problem of this study. What is required is the optimisation of the energy consumption of furnaces for different production loads and variation in fuel gas supply types. This section reviews the energy consumption optimisation models of reheating furnaces found in literature.

Fuel costs minimisation on a steel billet reheating furnace using genetic algorithms

Santos et al. modelled the operation of a reheating furnace as a non-linear optimisation problem with the goal of minimising fuel costs while still achieving the required temperatures. They used a developed genetic algorithms approach. The results indicated that it is possible to minimise costs for different charge temperatures and production rates using the implemented method [18]. Practical results of a specific scenario achieved a reduction of 3.4% in fuel consumption.

Considerations from the study are that a reheating furnace needs to maintain a specific temperature to heat the billets to achieve desired metallurgical and mechanical properties. The furnace load requirements change with production tempo and varying billet loading temperatures. Different product loads also influence the furnace heat and flow requirements. The use of an optimisation model reduces the processing time of the system.

The limitations of this model are that the furnace used did not have the ability to switch zones to other fuels. The system is also used to optimise a single furnace and not furnaces in a gas consumer network. The system uses thermodynamic equations to simulate what the required heat load of the billets inside the furnace are. This is not a simplified solution and requires extensive metering to properly implement.

Analysis of energy consumption and performance of reheating furnaces in a hot strip mill

Chen et al. analysed the energy consumption and performance of reheating furnaces in a hot strip mill. They used numerical predictions and practical measurements. Three heating

rates were simulated and compared for the numerical results. The results indicated that increased production is conducive to utilising fuel more efficiently. Practical measurements were used to determine the energy distribution and heat balance in the furnace. They focused on the heat recovery in the recuperating zone [52].

Considerations from the study are that increasing the yield of the furnace can increase fuel efficiency. Changing production rates have a marked effect on fuel rate in the furnace. The study varied production rates for typical, high and low heating rates. The study found a linear relationship between the yield of the furnace and performance efficiency [52].

Limitations observed in the study are the low variation in heating rates of the furnace. In practice, furnaces have many factors that influence production rates, such as unplanned breakdowns. Stable production and heating rates do not always occur. The study was also conducted on only a single fuel gas. The influence of different fuel sources was not simulated or measured.

Energy-efficient control of continuous reheating furnaces

Steinboeck et al. reviewed control strategies for reducing the energy consumption of continuous reheating furnaces. They analysed the energy flows and the efficiencies of these furnaces. The relationship between energy savings and emission reduction is discussed. A case study of an industrial slab reheating furnace shows how the implementation of a non-linear model predictive controller for the slab temperatures has reduced the primary energy consumption by 9.6% [53].

The study points out that control strategies can be implemented at low costs in a short period of time. Implementing an improved control strategy on a furnace can have a significant impact on the furnace energy performance. The controller used in the study replaced a strategy that has been used for decades.

The control strategies presented in the study are limited to certain operating conditions of the furnace. Control outside of normal operating conditions has not been optimised since each condition has its own optimum energy saving strategy. The controller cannot optimise the furnace in relation to other components in the network.

Optimisation of a slab heating pattern for minimum energy consumption in a walking beam type reheating furnace

Jang and Huang developed a mathematical heat transfer model to predict the temperature history of steel slabs in a walking beam type reheating furnace. The aim was to obtain the optimal heating pattern for the slabs to increase energy efficiency. An algorithm was developed to optimise the temperature distribution in the furnace zones. The results of the study were a lower energy consumption of the furnace compared to the original operating conditions. The largest saving was observed in the reduction of the preheating zone temperature [54].

What can be considered from the study is that the energy consumption in a furnace is closely correlated to the temperature setpoint. It is also important that the slabs exit the furnace at the correct temperature for rolling. The slabs need to be heated throughout the material core. This usually results in the overheating of the slabs in furnaces to simplify the operation of the plant. For this study application the furnace simulation will have to be adapted to operations where the furnace can utilise multiple fuel sources. The optimisation is also complex and does not account for operational changes.

Identification and improvement of operating practices of a reheating furnace to reduce fuel consumption in a hot strip mill

Chakravarty et al. analysed the operational practices of a reheating furnace of a hot strip mill. The aim was to improve the fuel consumption of the furnace. The furnace operation is dependent upon many external factors, such as mixing hot and cold slabs in the furnace charge, furnace pressure fluctuation, high waste gas temperatures, interruption of the furnace control system, insufficient gas supply and shortage of steel. They found that it is possible to reduce the impact of these external factors by coordinating the planning between the ladle furnaces, slab casters and fuel management services. The fuel consumption of the hot strip mill was reduced by 6.6% after completing the work [55].

The hot charging percentage was one of the major variables, and this was increased by improving the planning and operational practices. Management decided to include 100% of schedulable slabs produced in the rolling sequence, the hot condition had a major impact on the fuel consumption. Using statistical regression, the effect of individual parameters on production and fuel consumption was analysed [55].

These regression models were only used to point out dependencies in the system. The models only assisted the role players in highlighting the key areas of focus. The models were not used in any form of optimisation system.

Dynamic optimisation of a slab reheating furnace with a consistent approximation of control variables

Steinboeck et al. developed an optimisation model that can control the temperatures in a slab reheating furnace. They required a robust, accurate and low computational demand system. A key factor of the research was to solve the non-steady-state operating conditions. The system uses the furnace zone temperatures in a non-linear model. The optimisation method predicts the furnace and slab temperature trajectories [56].

This is a high-level model for temperature prediction in a furnace. It indicates that is possible to simplify a complex problem. The model was only demonstrated on a small scale and on a single furnace. The study did not focus on energy consumption, but more on the temperature requirements.

Efficiency analysis of radiative slab heating in a walking beam type reheating furnace

Han et al. developed a mathematical model to predict the thermal efficiency of a furnace by using radiative heat transfer. They used the heat balance of a sub-divided furnace model to calculate the temperatures of each zone. The objective was to calculate the heat transfer to the steel slab. They only considered the effect of the fuel feed ratio in the furnace and its effect on temperature. It is suggested that the model can be used to enhance furnace performance [57]. The primary focus of the study was not furnace energy efficiency, but temperature efficiency.

A soft-sensing method for optimising combustion efficiency of reheating furnaces

Wang et al. stated that the complexity of the combustion process control in reheating furnaces hinders efficient operation. They developed a soft-sensing method to predict the combustion efficiency since it cannot be directly measured. They implemented this model virtually on a reheating furnace. The key variables used were the air-to-gas and temperature-to-gas ratios. These variables were used to select and optimise an improved operating condition. They found that significant energy conservation could be achieved by using the method [58].

The study's focus is on temperature requirements and optimising the air-fuel ratio to improve the gas consumption around these requirements. It only looks at a single furnace's control philosophy for improved gas consumption. This is a simplified approach to optimisation, but the model requires multiple measurements of each zone in the furnace to optimise the system. Although it can be implemented in multiple furnaces, it does not consider the influence of other furnaces on gas consumption.

Walking beam furnace temperature control using a fuzzy feed-forward method in a steel rolling mill

Meixiang et al. proposed a new fuzzy feed-forward control method to obtain the required rolling temperatures in reheating furnaces [59]. They use the method to solve the temperature differences between the furnace zones. They highlight that a walking beam furnace is a complex system that is time-variant, has large delays, multiple parameters and is non-linear. They could minimise the temperature difference between the soaking and heating zone. This system requires a change in the control system of the furnace which requires large capital expenditure. The study does, however, only focus on the temperature control of the furnace and not on the energy consumption thereof.

Analysis of oxyfuel combustion as an alternative to combustion with air in metal reheating furnaces

Oliveira et al. analysed the option to use oxygen instead of air in the combustion process. They state that this topic is being widely discussed to reduce CO₂ emissions. They used a thermal simulation to analyse the effect of using oxygen with fuel to reach the same temperature requirements as with combustion in air. It was found that a significant reduction in energy consumption is possible with this approach. The cost of oxygen does, however, decrease the feasibility in furnaces with no heat recovery systems [60]. The study requires capital expenditure to implement which would reduce its viability in this study. There are also numerous safety requirements with the use of oxygen in combustion.

A numerical analysis of heating characteristics of a slab in a bench scale reheating furnace

Han et al. developed a numerical model to analyse the heating characteristics of a slab in a reheating furnace. They then compared the model results to experimental measurements from a steel production facility. They found that radiative heat transfer is the component in the numerical model which requires the highest accuracy, as it makes up the largest part of

the heat transferred [61]. The study focuses on the heat transferred to the steel slabs and does not consider the effect of energy consumption in the simulation.

Optimal control setting for complicated industrial processes and an application study

Wang et al. presented a method to optimise the control settings for integrated control of a walking beam reheating furnace. They found that the raw material quality influenced traditional optimisation models in cases where they cannot solve the problem. They state that most furnaces are non-linear systems and are difficult to model. They found that significant energy savings could be achieved using this method to optimise temperature control [62].

This model focuses on the optimisation of a single furnace temperature control. The effect of the fuel to the furnace is only taken for its heating value and not the effect on the furnace characteristics. This is a complex control system and not a simplified solution.

Optimal set values of zone modelling in the simulation of a walking beam type reheating furnace on the steady-state operating regime

Yang et al. developed a new mathematical approach for optimising the setpoint temperature values of a slab reheating furnace. The purpose of the study was to improve the current furnace optimisation method. They found that the new method decreases simulation time and the number of iterations required to solve the problem. The optimisation of temperature control in a reheating furnace leads to increased productivity and energy efficiency. The next step they propose is to use the model for an online dynamic optimisation control system [63].

The mathematical model proposed in the study is complex and requires detailed measurements from the furnace. The method also does not consider the effect of gas mixtures on the furnace.

Summary of reheating furnace energy consumption optimisation methods

This section reviewed numerous energy optimisation and procedures for reheating furnaces. Most of the research focuses on the improvement of temperature control optimisation from a production improvement perspective. The models do not focus on the effect of changing fuel sources throughout the production process. The models either have

low variability in production or they require detailed production information to simulate and optimise the furnace. These optimisation models also do not focus on the optimisation of the network of furnaces and their efficiencies.

2.3.5 SUMMARY OF RESEARCH FINDINGS

Limitations in existing research were found. Optimisation models that are available for the efficiency of an entire steel facility aim to improve different aspects of the plant. Some look mainly at the complete utilisation of the available thermal energy and suggest high capital expenditure improvements to the plant. Others look to improve the product flow to the same effect. Other studies recommend improved process control for a major impact on energy efficiency.

Research has been completed on the optimisation of the by-product gas distribution in steelmaking facilities. These models focus on the efficient distribution of by-product gas to boilers with improved control of the plant gasholders. These studies mainly use mixed integer linear programming (MILP) models for the optimisation of gas distribution with emphasis placed on penalty factors placed on control variables that streamline decision making in the model. The limitations in this research are that they require complex measurements from the steelmaking facility. They also only focus on the energy efficiency of boilers and their burners and not on other components in the facility. However, these studies form a good basis for the development of an optimisation model for the distribution of different gases to reheating furnaces.

Numerous studies were found that focus on the optimisation of reheating furnaces. Most optimisation models focus on the improvement of temperature control of a furnace. These studies do not focus on the effect of changing fuel sources on the furnace. Models are either limited to low variability in production rates or require complex measurements from the furnace to implement. All the models are implemented or analysed on a single furnace and do not consider the effect of the efficiency of other furnaces in the gas network. They do not optimise the gas consumption network as an integrated system.

The problem is that the operator cannot optimise the gas distribution network based on all the efficiency characteristics of the furnaces. An integrated network of the furnace energy characterisation models is required to optimise the by-product gas distribution. Such a gas distribution optimisation model has the following requirements:

- Give an optimised solution for the lowest cost of an integrated gas distribution network;
- Should be capable of optimising any operational configuration of furnaces;
- Can work with limited information from the plants; and
- Be simple and practical to implement on multiple furnaces.

The research question that arises from this section of the literature review on the optimisation of reheating furnaces is:

Can a characterised optimisation model simulate the gas distribution of multiple furnaces for the optimal cost?

The contribution of this study that was developed in Section 3.3 of the methodology to address these shortcomings is:

A new optimisation model of different gases in a gas distribution network.

2.4 Real-time optimisation models

2.4.1 HIGHLIGHTS OF THIS SECTION

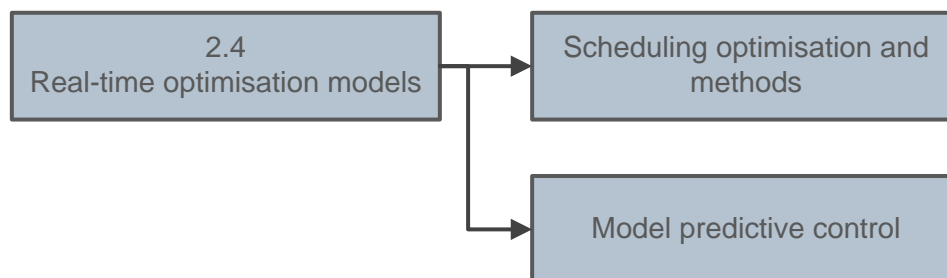


Figure 2-4: Overview of research on real-time optimisation models

In the previous section research was conducted on the optimisation models available for reheating furnaces and gas distribution networks. To improve control of the distribution of gas to the reheating furnaces in the network a real-time optimisation model would be able to assist a human operator in decision making. Real-time optimisation models that are reviewed in this section are shown in Figure 2-4. Optimisation systems and methods that have been developed for scheduling of production and energy in different industries are reviewed. Also reviewed are model predictive control systems that have been applied to reheating furnaces.

2.4.2 SCHEDULING OPTIMISATION SYSTEMS AND METHODS

Preamble

The first section of the review on real-time optimisation systems researched are scheduling optimisation systems and methods. What is required is a system that can assist an operator in deciding what is the most optimal distribution of gases to the reheating furnaces for the most cost-effective result. The effect of changes to the plant by-product gas supply also needs to be compensated for since steel plants are dynamic in their operations.

Scheduling and energy - Industrial challenges and opportunities

Merkert et al. discuss the challenges faced in an industrial environment regarding the scheduling of production around volatile electricity pricing structures. They cite the need presented by rapid changes in operating conditions behind the development of optimisation systems. They found that proper integration of production planning and energy management produce energy cost savings [64].

The system must integrate with production as well as real-time information to be able to react to changing conditions. The problem also requires advanced computing to perform optimisation operations. They also state the need for a well-designed user interface [64]. Their findings are useful for the development of a real-time optimisation system.

Modelling for integrated energy optimisation in cement production plants

Swanepoel developed an integrated optimisation system for the cement industry. The system uses production measurements to optimise the operational schedule of the plant to reduce the cost of electricity based on time-of-use tariff structures. The model considers other components and production buffers to optimise the production schedule. The model achieved good electricity cost savings. The author recommends the use of the system in other industries [65].

The model does not simulate the energy consumption of the components; only historical data is used to measure the performance of the system. The system uses the production buffers to optimise the schedule. In an integrated steelmaking facility, the gas storage buffers are not sufficient for this strategy.

A dynamic optimal control system for complex compressed air networks

Van Heerden developed a dynamic compressor selector for mining compressed air networks. The system calculates multiple compressed air setpoint for each compressor. It considers the location of the compressor and the demand of the network. From these multiple options, the compressors are dynamically selected. The system achieved electricity cost savings by supplying the network with the minimum network required compressed air [66].

A consideration that can be taken from the study is that the system considers the effect a compressor has on the network required compressed air. It calculates multiple solutions and selects the most effective one. The limitations are that the system does not, however, simulate the energy consumption of each compressor to select the most efficient one. The effect that changes on the network could have on the compressed air requirements can also not be predicted.

A two-stage method for solving the large-scale hot rolling planning problem in steel production

Tu et al. developed a method to solve and optimise the hot rolling planning of a reheating furnace. The problem has multiple constraints and objectives concerning planning. Some of the constraints are the product quality and not influencing rolling operations. They planned the rolling in two segments: for a single rolling unit and then for mixed rolling. The problem was then optimised by algorithms. They found the method to be effective [67].

This method only schedules the rolling sequence of the mill for the optimisation of hot charging to reduce fuel consumption. It is only used on a single reheating furnace and does not consider the effect on the gas network. The model does not predict the fuel consumption of the furnace.

Simultaneous optimisation of slab permutation scheduling and heat controlling for a reheating furnace

Suzuki et al. propose a modelling method that simultaneously optimises the feed scheduling of slabs and the temperature control of the reheating furnace. They state that the system is a hybrid of two separate models. They simplified the modelling of the furnace to achieve reduced computational time. They state that the method can support the use of a more complex model and that the model needs to be verified on a real reheating furnace [68].

The main purpose of this model is to optimise the temperatures of the slabs in the furnace for an improved control system. The model does not consider the effect of fuel consumption and was not tested on a network of furnaces.

Summary of scheduling optimisation systems and methods

This section reviewed available systems that can optimise schedules or other operational parameters in real-time or provide methods that will be able to with some adaptations. The review found some limitations regarding the required application to this study's problem statement. The systems reviewed do not simulate the energy consumption of the component's schedules optimised. Some systems rely on production buffers that are not sufficient in steelmaking facilities. These systems do not consider the effect of other components' energy efficiency on the optimisation results. They also cannot simulate supply changes on the system. What is required is a system that can assist a human operator with the optimisation of the gas distribution to the reheating furnaces. This must be done by simulating the optimised energy consumption in real-time.

2.4.3 MODEL PREDICTIVE CONTROL

Preamble

The final section of the review on real-time energy optimisation systems is research on model predictive control of reheating furnaces. These models look to optimise the control of reheating furnaces based on calibrated prediction models. What is required is a system that can simulate the optimised gas distribution to reheating furnaces operating in a network.

Mathematical model-based control system for silicon steel mill of the Rourkela steel plant

Goswami et al. developed a control system for a silicon steel mill furnace based on a mathematical model. They combined a decarburisation model and a thermal model. The model considers the line speed of the furnace as well as various characteristics of the steel itself. The different temperatures in the zones and the flow of the process gas are taken as inputs. The model predicts the temperature profile as well as the carbon composition of the steel in the furnace. The model suggests a setpoint for the line speed and temperature setpoints of the furnace. They improved the decarburisation of the steel in the furnace [69].

The model requires detailed measurements from the furnace and ties in with the control system. It is not a simplified solution. It also does not take the effect of gas consumption into account. This is a single furnace temperature optimisation model and system.

Application of close loop expert system for heating control of rolling mill furnaces in a steel plant

Gangadaran et al. developed an expert control system that can predict the optimal temperature requirements of an annealing furnace. The model is used to control the furnace to achieve the required product quality. The expert system is described as improving the control of the temperature as if a process expert were present in the control room. They were able to enhance the plant efficiency in terms of production output, quality and energy [70].

The system enhances the control of the temperature of the steel in the furnace. It operates in real-time. It requires detailed information from the furnace and operates directly in the furnace control system. Implementation of the system requires capital expenditure. It does not provide an energy prediction model for the furnace. It also operates on a single furnace and does not operate in a network with variable gas supply.

Non-linear model predictive control of a continuous slab reheating furnace

Steinboeck et al. designed a non-linear model predictive control system for a reheating furnace. The model was developed from first principles and sets the furnace temperatures to achieve the required final temperature in the slabs. The model is suitable for non-steady-state operations and can achieve user defined slab temperature profiles. The model considers the furnace as a continuous process. They found the controller to be reliable and accurate [71]. The system does not set any energy requirements for the furnace. It is also only applied to a single furnace, requiring multiple measurements from the furnace control system to operate.

An adaptive neural network model for predicting the post roughing mill temperature of steel slabs in the reheating furnace

Laurinen et al. developed a method to predict the slab temperature after it has passed through the roughing mill. The method uses neural networks of the temperatures of the slabs in the reheating furnace. They implemented the model on a production and found it

to be reasonably accurate. However, certain slabs had larger prediction errors. They require more input data for the time delays after the furnace to improve on the errors [72].

The model requires complex measurements from the furnace to implement. It also only calculates the slab temperatures and does not consider the energy required to heat the slabs. It also only controls a single furnace.

Model-based trajectory planning, optimisation, and open-loop control of a continuous slab reheating furnace

Steinboeck et al. developed a temperature control method for a reheating furnace. They developed the system based on a simple, accurate and robust control structure for furnaces that can be used in real-time. The method predicts the temperature requirements for individual slabs and then plans the zone temperature setpoints for the furnace. The system can be used for a control system and they provide an example of the system use [73].

The control system is suitable for real-time use. However, the control system only predicts the temperature requirements of the slabs in the furnace and does not provide the gas requirements of the furnace. It optimises the temperature requirements of an individual furnace and does not consider the integrated effect of gas consumption on the distribution network. The system requires complex operational measurements from the furnace.

Dynamic furnace temperature setting research on the combustion system of a rolling mill reheating furnace

Wanli et al. analyse the factors that influence the setting of temperature setpoints in a reheating furnace. They highlight that these factors are an industry-wide phenomenon. This includes production rhythms and furnace thermal characteristics. They theoretically analyse the effect on the temperature setting with an energy balance and they verified their results with experimental data. They found that by dynamically setting the furnace setpoints significant energy savings could be achieved [74].

This method only analyses the effect of the changing temperatures on a furnace and a real-time system is yet to be developed. The strategy cannot simulate the reheating furnace energy consumption. It does not consider the effect of changes on the gas supply to the furnace, only the effect on production tempo. Although the solution is simplified, it does require complex measurements for the furnace.

Siroll furnace optimisation

Siemens VAI provide a complete hardware and software solution that controls a reheating furnace optimally for reduced energy consumption. The system takes complete measurements of the furnace to dynamically control the temperature setpoints of the furnace for optimal product discharge temperatures. The system considers typical delays that occur in the production process. It optimises the start-up and idling sequence of a reheating furnace [75].

The system requires a complete overhaul of the furnace control system, which is a large capital expenditure option. The system does not, however, consider the efficiency of different fuel gases in the furnace. It also does not consider the effect of gas supply shortages on the furnace. This solution is only implemented on a furnace as an individual system and does not consider the effect of another furnace in the gas consumption network.

Summary of model predictive controllers for reheating furnaces

Model predictive controllers were reviewed in this section. They were found to be suitable for the real-time control optimisation of reheating furnaces. However, these systems focus on the improvement of temperature control. They also require complex measurements for the furnaces and in some cases high capital expenditure costs to implement. These systems are only suitable for optimising a furnace as a single entity and not for furnace networks.

2.4.4 SUMMARY OF RESEARCH FINDINGS

Limitations were found in existing research. Production scheduling systems do not simulate the effect of energy consumption of the components. They rely on production scheduling or buffers to shift load to other time periods for energy cost improvements. The systems that do operate in a network, do not consider the effect of other components' effect on the network energy efficiency. They also cannot simulate the effect of changes to the system.

Model predictive control systems require complex measurements from the reheating furnace to operate. In multiple cases, they are suitable for real-time use. They focus on the prediction and improvement of the temperature setpoints and not the effect on energy efficiency. These systems work on a furnace as a single entity and do not work as an integrated network of furnaces for improved control of the gas distribution network.

The problem is that the operator cannot optimise the gas distribution network based on all the efficiency characteristics of the furnaces. A real-time optimisation system is required that optimises the by-product gas distribution network with an integrated network of furnace energy characterisation models. Such a real-time system has the following requirements:

- Must be able to simulate the gas consumption of the network in real-time;
- Optimise the plant gas distribution in real-time;
- Provide useable information to the operator in real-time;
- Simulate and optimise the effect of changes in gas production on the network;
- Be practical to implement on an integrated steelmaking facility; and
- Require low capital expenditure to implement.

The research question that arises from this section of the literature review on the real-time optimisation systems for reheating furnaces gas distribution is:

Are real-time gas network distribution optimisation systems available and practical to implement?

The contribution of this study that was developed in Section 3.4 of the methodology to address these shortcomings is:

A real-time optimisation system for gas distribution optimisation.

2.5 Summary

This chapter consisted of a literature review of current research and work. The topics covered are energy modelling of reheating furnaces, optimisation of reheating furnaces and real-time optimisation systems.

An overview of the different energy models of reheating furnaces is provided, such as benchmarking and energy intensity models. Benchmarking of energy consumption and energy intensity modelling use predominantly energy per tonne models for comparisons. These models are too simple to allow for variation in production rate and are not developed for different gas mixture ratios. They can also not simulate energy on a frequent basis.

Software tools that are available require complex measurements like the geometry for the furnace. They provide static feedback that can be used to make design changes to the furnace. Adding on to this are CFD models, these systems require complex measurements and long computation times. This means that they do not allow for frequent changes of input parameters like fuel gas mixtures. They are not simple furnace models.

The simulation models found in literature all require detailed information to simulate furnace parameters at varying production rates. However, these parameters focus on furnace schedules and temperature setpoint modelling and not energy consumption.

Optimisation models that are available for the efficiency of an entire steel facility aim to improve different aspects of the plant. Some look mainly at the complete utilisation of the available thermal energy and suggest high capital expenditure improvements to the plant. Others look to improve the flow of product to the same effect. Studies recommend improved process control for a major impact on energy efficiency.

Most optimisation models focus on the improvement of temperature control of a furnace. These studies do not focus on the effect of changing fuel sources on the furnace. Models are either limited to low variability in production rates or require complex measurements from the furnace to implement. All the models are implemented or analysed on a single furnace and do not consider the effect the efficiency of other furnaces in the gas network. They do not optimise the gas consumption network as an integrated system.

Production scheduling systems do not simulate the effect of energy consumption of the components. They rely on production scheduling or buffers to shift load to other time periods for energy cost improvements. The systems that do operate in a network, do not consider the effect of other components' effect on the network energy efficiency. They also cannot simulate the effect of changes to the system.

Model predictive control systems require complex measurements from the reheating furnace to operate. In multiple cases, they are suitable for real-time use. They focus on the prediction and improvement of the temperature setpoints and not the effect of energy efficiency. These systems work on a furnace as a single entity and do not work as an integrated network of furnaces for improved control of the gas distribution network.

The novel contributions of this study are highlighted in each section of the literature review conducted. The limitations of current research and how it relates to the research motivation

and objective were discussed. The limitations are used to derive three research questions that are addressed by the work in this study.

The three research questions derived from this study are combined in the development of a methodology in the next chapter. The simplified furnace energy consumption models are required in the simulation of a gas distribution network. The simulation can then be used in the development of an optimisation model of energy consumption for multiple reheating furnaces. Finally, the optimisation model is required for the development of a real-time optimisation system for the gas distribution to the reheating furnaces.

3 METHODOLOGY



Reheating furnace.⁶

⁶ Hydrosol System, Inc., *Reheat furnace*, 2017 [Online]. Available: <https://hydrosolsystem.com/reheat-furnace>. [Accessed 8 October 2017]

3.1 Preamble

In the previous chapter, a literature review was conducted. The background was provided on steel production facilities with the focus being placed on reheating furnaces. Energy modelling and optimisation methods in the industry were discussed. The considerations and limitations made for this study were gathered from the reviewed literature.

The findings are used in this chapter to develop an optimisation methodology. The methodology requires the following steps:

- The furnace behaviour is studied to develop furnace energy characterisation models;
- The models are configured in a gas distribution network and used to develop an optimisation algorithm;
- The algorithm together with the furnace characterisation models is used to develop the scope of a system that can be used by a steel production facility; and
- A method is developed to quantify the benefit of the optimisation system.

3.2 Furnace energy characterisation model

3.2.1 TYPICAL REHEATING FURNACE MEASUREMENTS

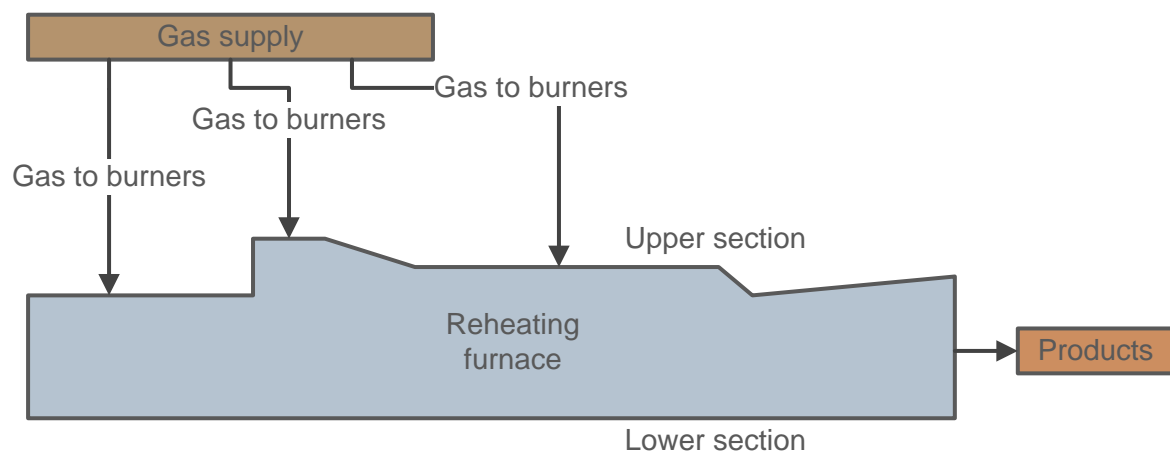


Figure 3-1: Basic layout of a reheating furnace

The characterisation of a reheating furnace requires certain operational information. A typical layout of a reheating furnace can be seen in Figure 3-1. The furnace reheats material to a temperature where it can be shaped into different final products by a mill. Gas is supplied to the furnace burners by a gas network. Burners can be located at the top and

bottom of the furnace. The furnace is further divided into different sections. Most commonly a furnace has preheating, heating and soaking zones.

The most important measurement in the energy characterisation of the furnace is the gas flow to the various furnace zones. Gas flow measurements are critical to the operation of the furnace as they are used to control the gas flow required by the furnace. The furnace gas flow is measured in cubic meters per hour [m³/h]. Each zone is usually measured separately with a totalizer providing a total furnace gas flow consumption measurement.

It is possible to operate a furnace on multiple gases, depending on the fuel gases available on the plant. Fuel gases from process by-product gases can include Coke Oven Gas (COG), Blast Furnace Gas (BFG) and BOF gas. Other gases can be purchased, such as natural gas and Liquid Petroleum Gas (LPG). Each zone in a furnace operates its burners independently from the other. This means that burners operate on a single gas at a time, but that different zones can be operated on other types of gas. The furnace burners can be designed to operate on a single gas while other burners in the same furnace can operate on multiple gases.

Another important measurement in a furnace is the temperature in each zone. The temperature is used to control the gas supply to each zone. When temperatures drop in a certain zone more gas is sent to the burners to reach the set temperature. Similarly, when the temperature is reached in a zone the gas to the burner will be cut back. The temperature setpoints throughout the furnace are very important for the furnace operation, as it is used to reach the target temperatures of the material in the furnace for further production.

The gas burned in the furnace also has characteristics. The most important of this is the gas Calorific Value (CV) measured in megajoule per cubic meter [MJ/m³]. The gas CV value indicates the energy present in the fuel. This is further used to convert the gas flow to the furnace into an energy value. The energy value, measured in gigajoule [GJ], is what will be used in this methodology to develop a furnace characterisation. Energy is calculated using Equation 3-1. Where energy (E) is calculated by multiplying the volumetric flow (\dot{V}) with the CV value of the gas.

$$E = \dot{V} \times CV \quad 3-1$$

The measurements that are used to develop the furnace energy characterisation model need to be verified. Good data is critical when any simulation model is created. A simulation can only predict a system as accurately as the data set allows. Verification takes place by measurement instrument calibration. Care needs to be taken when using measurements from an industrial facility. It needs to be ensured that the proper processes are in place to keep the measurements accurate. Usually, an industrial facility has set procedures in place to intermittently calibrate measurement equipment in reheating furnaces.

3.2.2 FURNACE OPERATIONAL CHARACTERISTICS

Reheating furnaces are dynamic consumers of energy. There are numerous factors that influence the operation of the furnace. This means that there are operational characteristics of furnaces that influence its energy consumption. Some of these operational characteristics are listed in this section.

The main purpose of using a reheating furnace in an industrial facility is to reheat cold stock for further processing. The production output of a furnace is, therefore, the most important characteristic of a furnace. Most performance figures of a furnace are coupled to its production output in some way [12].

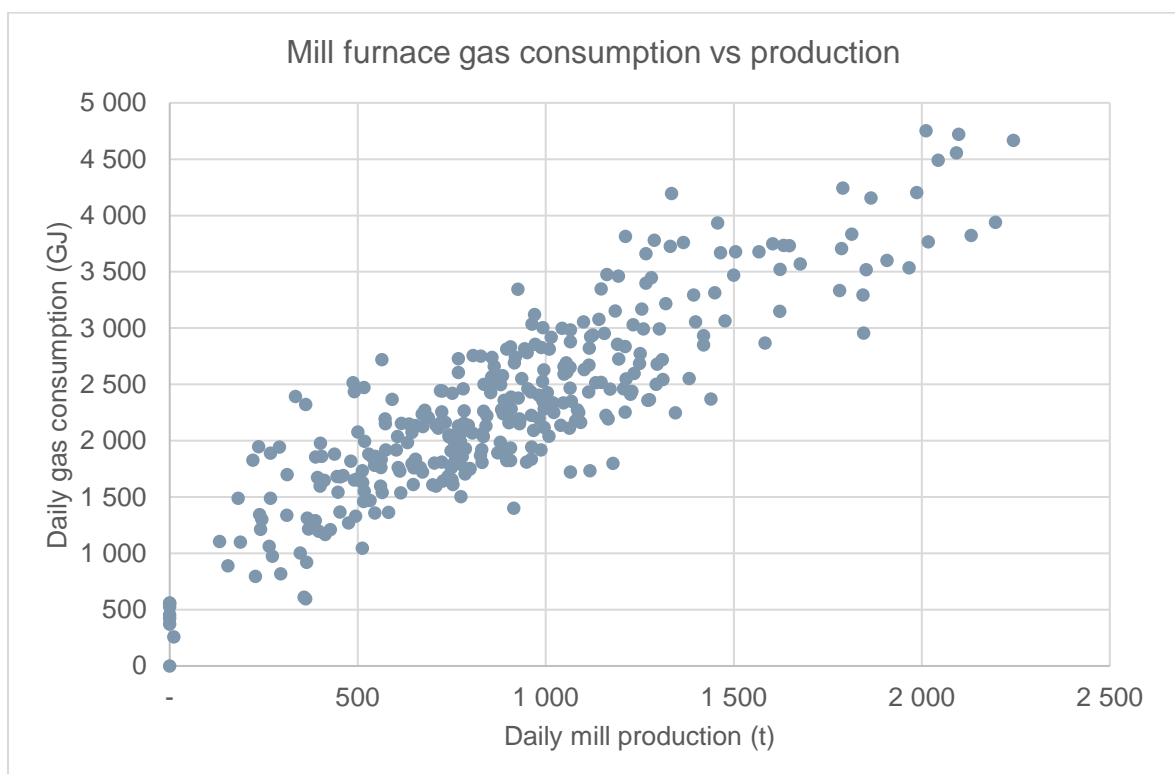


Figure 3-2: Daily furnace energy consumption vs production

Figure 3-2 shows typical daily furnace production against its total gas energy consumption. As can be seen in the figure there is a clear linear correlation between production and energy consumption. Higher daily production values require more energy to produce. Similarly, lower production values consume less gas energy per day.

It can also be seen that the furnace does not produce the same tonnage per day. This can be expected as production rates are dependent on many factors, one of which is the production of different steel profiles that play a large role in varying production rates. The rate at which varying steel profiles are rolled or produced is different due to profile size and shape. Larger profiles, like rails, are typically rolled slower than smaller profiles, like wire.

There are planned production delays that slow down or stop production. This includes planned maintenance that can be scheduled on the plant. This is usually done on a weekly basis. Even market conditions influence the production rate of the furnace as less or more steel is required from the plant.

Other factors that can influence production are unexpected production delays. This can be caused by numerous factors. Breakdowns of equipment is a major factor; the furnace production rate will be slowed down as the necessary repairs are made on the plant. The breakdowns are not limited to the specific plant, as breakdowns on either upstream or downstream processes can delay the plant production. Factors include delays or shortage of steel from upstream suppliers. Or delays in downstream processes.

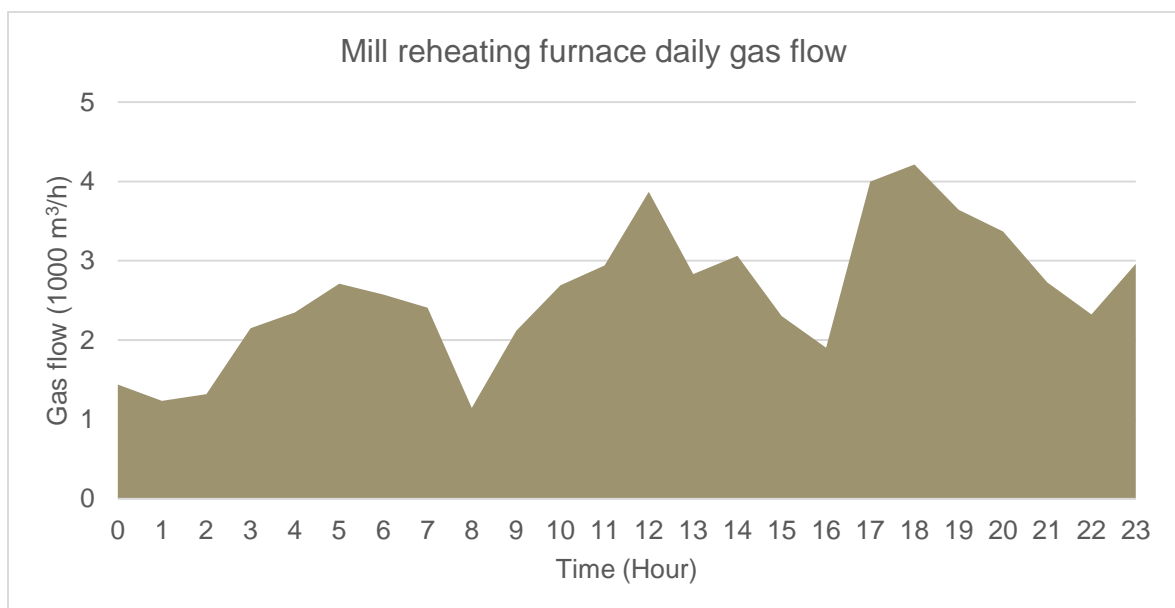


Figure 3-3: Furnace daily gas consumption flow

All the factors mentioned influence the production rate of the furnace. Ideally, a furnace would produce steel at a constant rate. But these planned and unplanned factors affect the furnace intermittently. The furnace does not produce at a constant rate throughout the day. A typical production day is illustrated in Figure 3-3 where the reheating furnace gas consumption, in 1000 m³/h, is plotted over the course of a day. It is clear that the furnace gas flow consumption changes continuously throughout the day. This means that the energy consumption throughout the day is not constant.

The furnace operational characteristic is also influenced by the gas it consumes. The furnace and its burners are designed to operate on a specific gas as fuel. Gas availability may necessitate the use of an additional gas type. This means that more than one gas type can be consumed by the burners. Different gases have different characteristics like density and pressure, which in turn have an influence on the way the furnace operates.

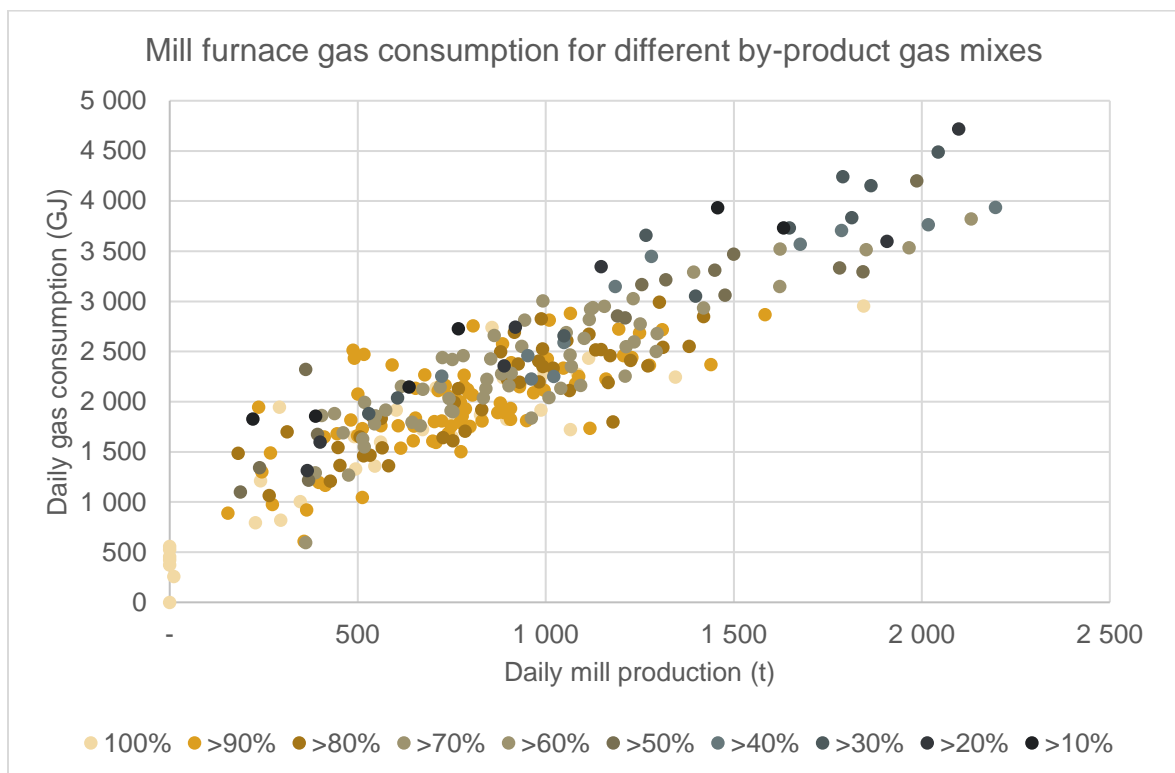


Figure 3-4: Daily furnace energy consumption vs production for differing by-product gas mixtures

Figure 3-4 shows the same data as in Figure 3-2, with the gas consumption being grouped by the amount of by-product gas in the mixture to the furnace. The furnace can consume by-product gas, in this case, Coke Oven Gas (COG), and natural gas. The consumption is grouped in 10% intervals of the amount of by-product gas in the total gas energy

consumption mixture of the furnace. At 0% the furnace is operated on natural gas, at 100% the furnace is on full COG operation.

It can be seen from Figure 3-4 that there is a difference in energy consumption when the gas mixture to the furnace changes. As the furnace is designed for COG, consumption appears to be lower when the furnace is burning this gas. When the furnace is operating on natural gas the consumption is higher for the same production figure.

3.2.3 DEVELOPING FURNACE CHARACTERISATION MODEL

All the factors mentioned in the previous section need to be taken into consideration when developing a new furnace energy characterisation model. There are numerous factors that influence the rate of production during the day to day operations of the furnace. The furnace operational characteristics change as different gases are consumed by the furnace. A characterisation model will need to be able to adapt to changing furnace demand and gas supplies.

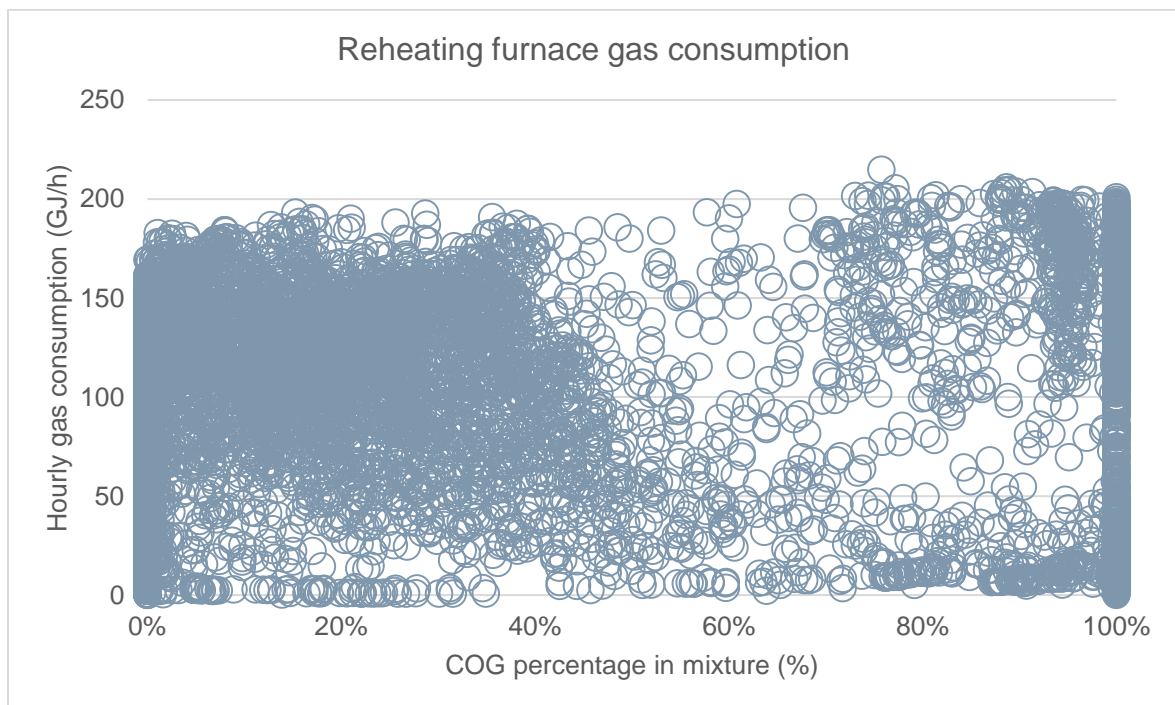


Figure 3-5: Furnace gas consumption per hour vs COG in the mixture

The method developed in this study to characterise the furnace gas consumption is to plot the energy consumption vs the COG in the energy mix. Figure 3-5 illustrates this proposed model that plots these values at hourly intervals. It can be seen that there is a maximum

energy consumption that the furnace can demand from the network on a specific gas type. In this case, the furnace consumes more energy when operating on COG. This is due to the furnace not being capable of consuming natural gas in its preheat zone.

What is also apparent from displaying the data as in Figure 3-5, is that there are certain areas where the furnace does not operate frequently. This is due to the difference in size of the various zones. In this case, the heating zones are the large gas consumers. The furnace zone gas selection is changed by an operator. Their experience is used to determine which zones should be operated on a different gas when a change is demanded.

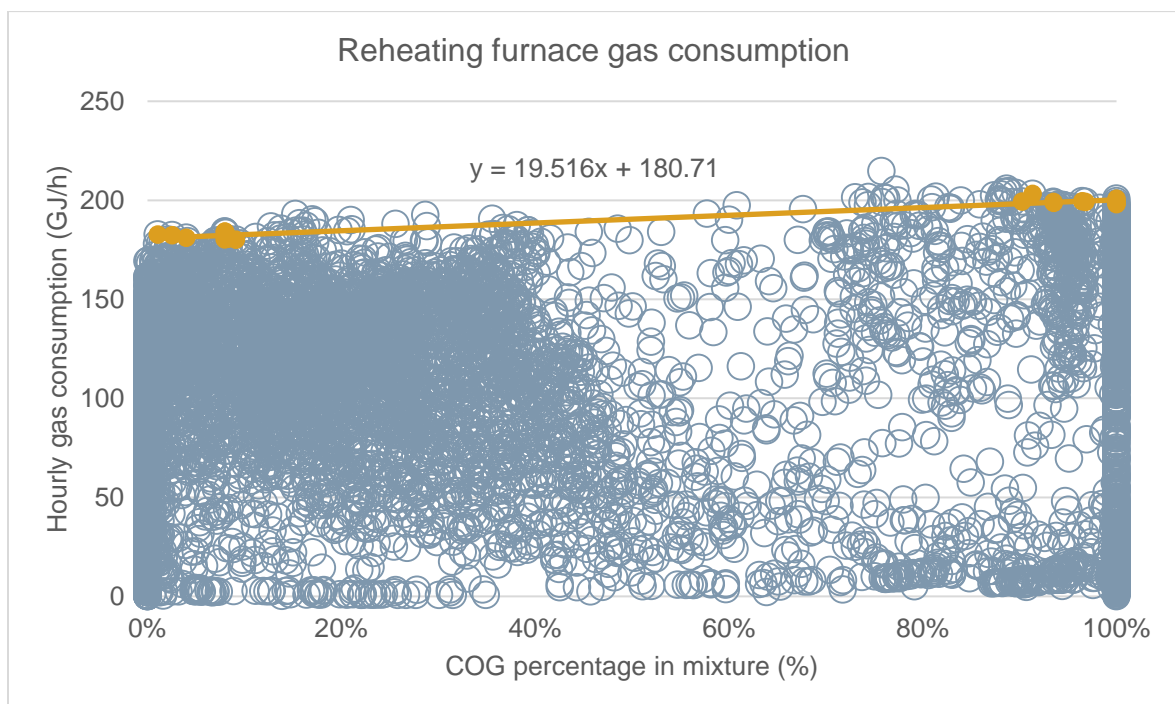


Figure 3-6: Maximum furnace gas consumption per hour vs COG in the mixture

In most cases, the furnace is either operated on full COG or full natural gas. Using this for the characterisation of the furnace the maximum load of the furnace can be plotted. The maximum gas consumption of the furnace between 0-10% and 90-100% is marked in Figure 3-6. The top 10 points in each interval are used to develop a regression line for the furnace maximum load. The furnace maximum energy consumption ($E_{Maximum}$) at a specific gas mixture percentage (x) can then be calculated with equation 3-2. Where m is slope and c is the intercept of the regression line.

$$E_{Maximum} = mx + c \quad 3-2$$

3.2.4 SIMULATING VARYING FURNACE GAS CONSUMPTION

This section uses the method developed in the previous section to simulate different parameters of the furnace. The maximum energy consumption can be determined at different values of furnace gas mixture. The model can also be scaled to varying loads pulled by the furnace. This will be needed when configuring gas consumers in a network. The model will be used to simulate changes in the network.

The model can determine the load of the furnace at different mixtures of COG and by-product gas. This is achieved by changing the value of x in equation 3-2. The simulation can be used to estimate the gas consumption of the furnace at varying gas mixtures. By varying the gas mixtures, the effect of the change on a furnace can be determined and the redistribution of gas can be planned.

$$E_{Load} = Load_{Furnace} \times E_{Maximum} \quad 3-3$$

The model can also be adjusted to scale to varying furnace loads. There are many factors that can influence the rate at which the furnace consumes gas as is mentioned in the previous section. It is important that a simulation model can adapt to changes in the furnace gas demand. This is done by building a factor of the maximum furnace work load into the simulation model. This is done by using equation 3-3, where the energy consumed at a specific furnace load (E_{Load}) is calculated by multiplying the energy of the furnace at maximum load ($E_{Maximum}$) with the load of the furnace ($Load_{Furnace}$). The furnace load is a percentage of the maximum load at a specific time, this ranges from 0% to 100%, but it is possible for the furnace to exceed the maximum load at extreme high production rates or loads. The simulation will use this factor to scale the energy consumption accordingly.

An example of a furnace energy simulation is illustrated in Figure 3-7. The furnace is receiving gas at a ratio or gas mixture of 40% COG. The furnace load or production rate is simulated at 60% of the maximum gas energy consumption. In this case, the inputs were provided for the furnace energy consumption simulation, but the purpose of the model is to use inputs from the actual consumption of the furnace and scale it to a new gas mixture. This will be used to determine what the impact of changes to the furnace will be on the energy consumption.

The furnace gas consumption cost calculation is done by using the gas mixture and the simulated energy consumption. This is needed to determine the best possible cost

operational point of the furnace with its current network constraints in place. This will be based on gas availability as well as the status of other consumers in the network. This will be discussed in greater detail in the following sections.

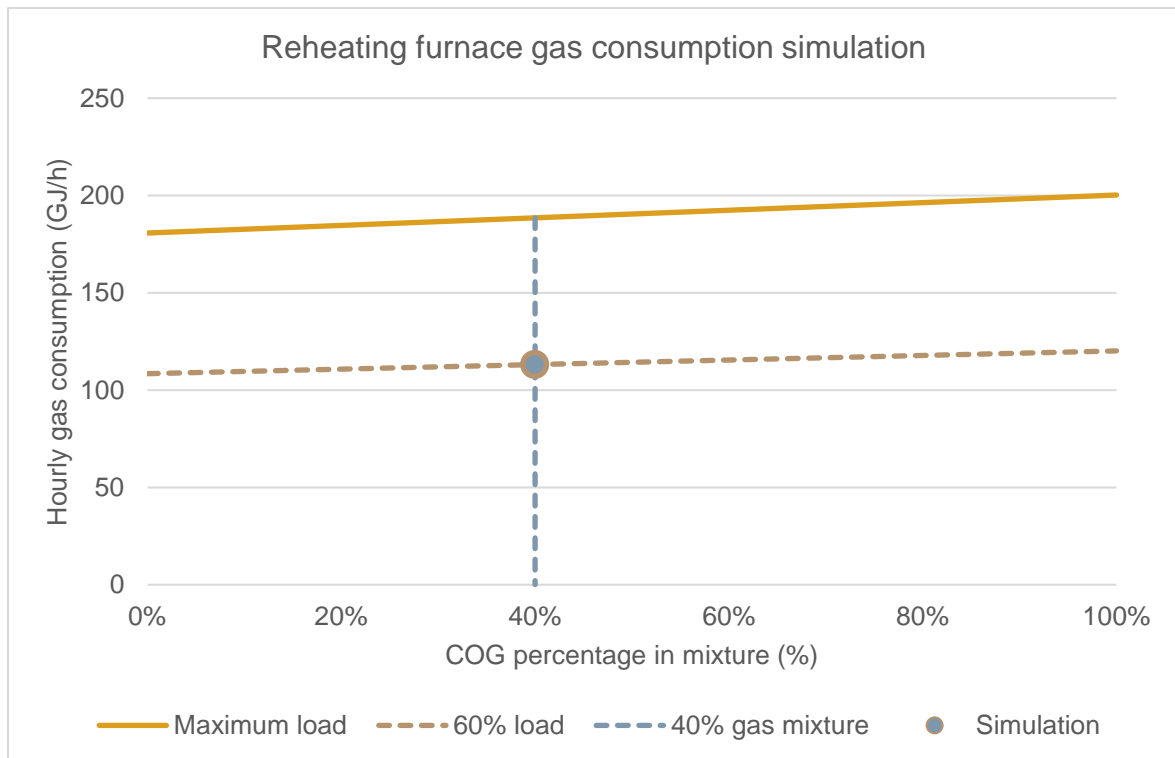


Figure 3-7: Reheating furnace energy simulation example

3.2.5 MODEL VERIFICATION PROCEDURE

When using any simulation model, the accuracy of the model should be verified. The suitability of the furnace energy consumption simulation model must be tested before it is implemented in any application. To achieve this, it is suggested that a series of characterisation tests are done on the furnace.

The procedure suggested for performing characterisation tests on the furnace is:

- Determine the various energy sources of the furnace and burners;
- Establish what zones are present in the furnace;
- Mark which zones and burners can be operated on different fuel sources;
- Map all the different combinations of gas usage to each set of burners; and
- Operate the furnace on all configurations for a period at a constant production tempo.

The characterisation tests are necessary to verify the relationship of the furnace at the same load at the same production conditions, on varying gas mixtures. The model suggests a linear relationship in the consumption of energy at varying fuel gas mixtures. The simulations are performed accordingly, as is shown in Figure 3-7. In the next section, the furnace energy characterisation models developed are used to develop a gas network optimisation model.

3.3 Gas distribution network optimisation model

3.3.1 CONFIGURING FURNACE MODELS IN A NETWORK

In a typical industrial plant, there can be multiple gas consumers. Each consumer has its own characteristics and operational constraints. The furnace energy simulation model developed in the previous section can be configured in a gas consumer network. This can then be used to simulate the gas consumption of the consumers in the network.

Figure 3-8 shows a typical gas network layout of an industrial facility. In an integrated steel production facility, it is possible to have multiple by-product gas sources. In this example, there are a blast furnace and coke plant. These components produce Blast Furnace Gas (BFG) and Coke Oven Gas (COG) respectively. Other fuel gas sources can be supplemented from outside the facility, in this case, natural gas.

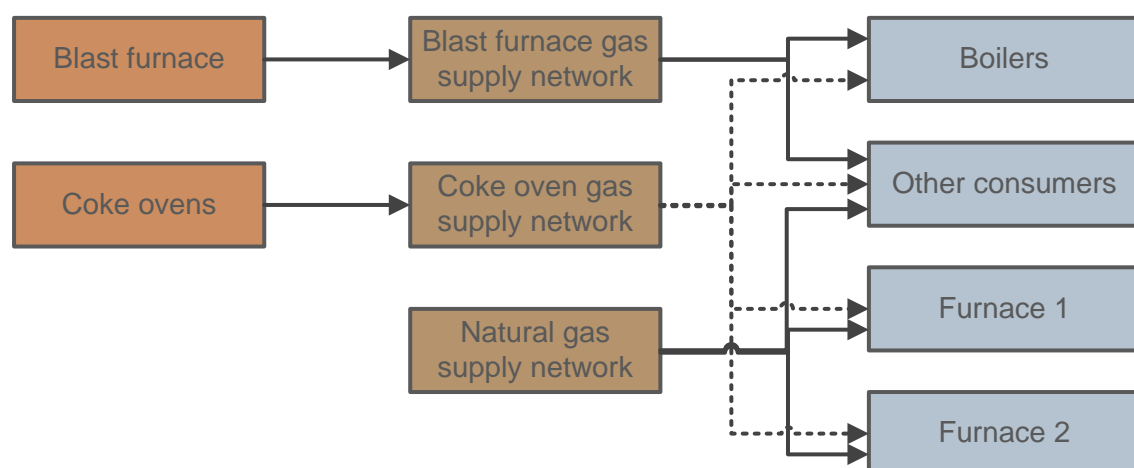


Figure 3-8: Basic gas supply and consumer layout

These gases typically have a complex gas distribution network to transport the gas to the different consumers. The network would require gas lines to transport the gases to the consumers. The gas supply must also be controlled at a certain operational pressure. This

is usually controlled by gasholders to keep the pressure stable and to act as a buffer for unstable and unpredictable gas supplied. When the pressure in the network or the gasholder level gets too high, the gas is typically burned off in a flare stack until it reaches acceptable pressure control levels. Not all plants have gasholders available. These types of networks are controlled by the line pressure by only using the flare stacks.

The plant can distribute these fuel gases to different consumers as necessary, required or available. Integrated steel production facilities can have multiple gas consumers. The consumers can be designed and configured to operate on different fuel sources. In the example in Figure 3-8, the plant gas consumers are boilers and furnaces, as well as other plant consumers.

The gas suppliers in the network can be irregular in their supply. This causes supply shortages or excess of fuel gases. Coupled with the instabilities of consumers discussed in the previous section, a network is prone to be unpredictably variable. This is typically the cause of the need for a supplemental fuel gas.

The need for fuel switching is also necessary for this reason. The fuel distribution to the network consumers is controlled manually by an operator. The operator has many variables to deal with in the daily operation of the plant. The need for optimal fuel switching, due to all the constraints mentioned in this section and the previous, is the core of this study.

3.3.2 FURNACE CHARACTERISTICS IN A NETWORK

The main consumer considered in this study are reheating furnaces. These components are influenced by many different events and situations. These events have a direct impact on the energy consumption of the furnace. Some of the events are predictable and planned, others are intermittent and unpredictable. All have adverse effects on the reheating furnace and plant. The events will be discussed in this section.

Steel milling plants can produce many varying steel products and profiles. These profiles are produced at varying production rates due to their different sizes and speeds they can be rolled at. The rate at which gas is consumed by the furnace is also closely correlated to the production rate, as was discussed in previous sections. When multiple furnaces are in a network the rate at which they all consume gas will most likely be different.

Industrial facilities operate constantly, usually with very little downtime available. This causes a large amount of strain on machines to constantly operate. It is, therefore, necessary to schedule regular maintenance stops to keep the plant operational. Plants usually stop for planned maintenance once a week. When this occurs at a steel mill, the furnace is usually idled at a lower than normal temperature until maintenance is complete and normal operation can resume. The furnace will consume less gas as the heating rate required is lower and no production occurs.

When work is necessary on the furnace itself, longer duration maintenance periods are required. The furnace takes about two days to cool sufficiently for work to take place inside the furnace. The furnace will not consume any gas during these periods. This is usually not a regular occurrence and is planned long before the maintenance is scheduled.

With the plant being under strain due to constant operation most of the time, breakdowns unfortunately occur. This causes unplanned shutdowns of the plant's affected machinery. The time that it takes for the machinery to be repaired varies significantly. These unplanned stops are the most difficult to plan for. The furnace operator usually queries other personnel on the plant to determine the extent of the delay. Using this information, the operator can decide if it is necessary to idle the furnace or to keep the current temperature setpoint.

3.3.3 OPTIMISATION MODEL

There are numerous factors that influence the gas consumption of consumers in a network. The gas consumption characterisation model that was developed in the study can be used to simulate the energy consumption of the network. All the constraints mentioned in the previous sections can now be used to optimise the gas consumer network. In a network where consumers vary in efficiency, it is possible to optimise the fuel switching between gas consumers. An optimisation model is used in this section, as is shown in Figure 3-9.

The optimisation model in Figure 3-9 shows an example of the optimisation of fuel switching of by-product and purchased gas between two furnaces. The optimisation model uses the furnace model developed in Section 3.2 to find the least expensive distribution of gas in a network. All by-product gas must be consumed in this model as this is produced by the plant and not purchased from a utility or service provider. This is done by iterating through all furnace gas mixtures possible in the network.

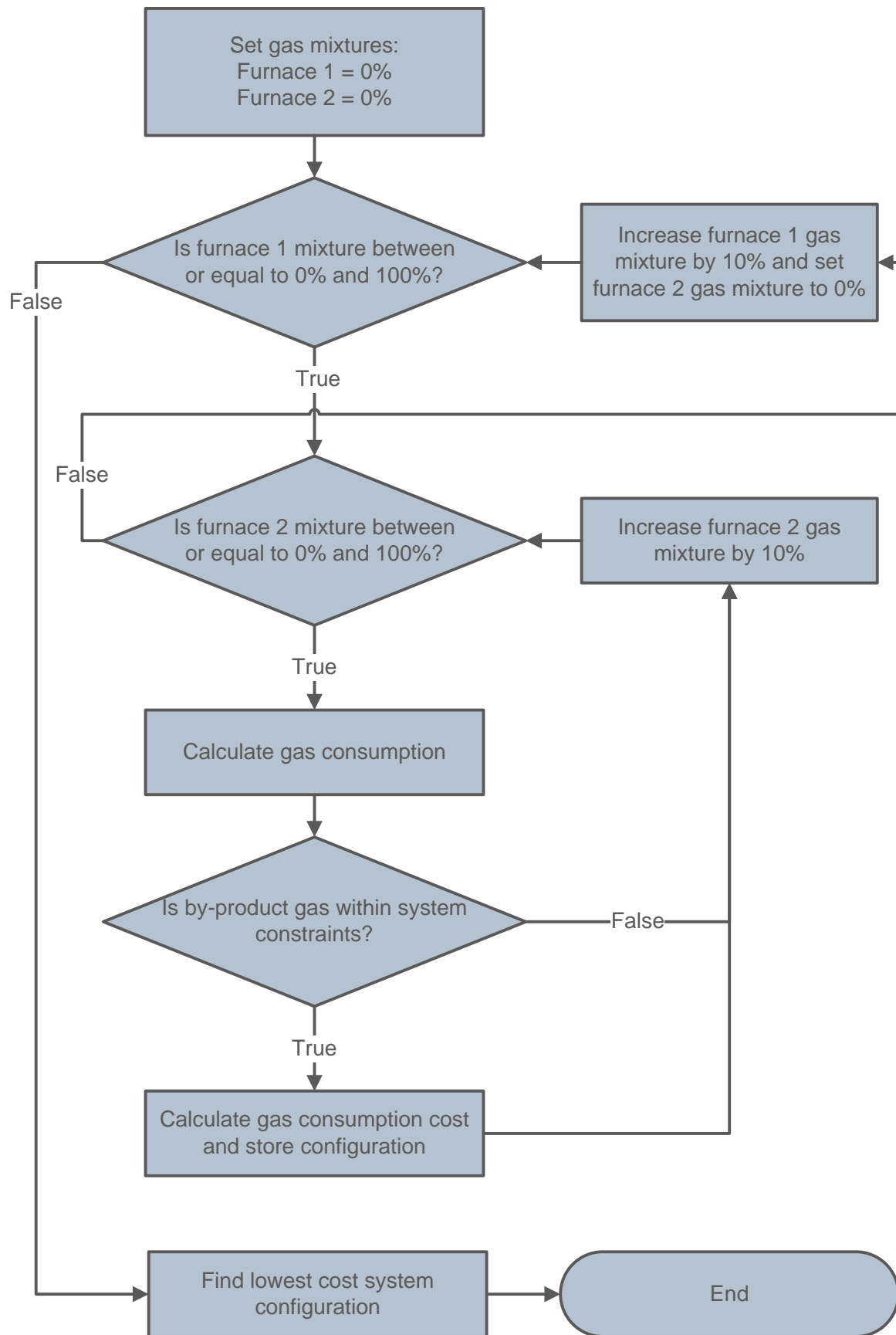


Figure 3-9: Flow diagram of the gas optimisation model

The model starts by setting the mixture of by-product gas of both furnaces to 0%. There are limits in place to check if the furnaces' mixtures are between 0% and 100%. The network gas consumption is calculated for the set mixtures. The system is then checked against constraints. There is a check in place to determine if the amount of by-product gas consumed does not exceed the amount available in the network. Another check is that the amount of purchased gas does not increase. If the system passes the constraints set, then the cost of the solution is calculated and stored.

If the solution does not pass the system constraints, then the second furnace gas mixture is increased by 10%. The previous process is then repeated until the second furnaces' gas mixture exceeds 100%, which is not possible. Furnace two's gas mixture is reset to 0%, after which furnace one's gas mixture is increased by 10%. The process until now is then repeated until furnace one's gas mixture exceeds 100%, which is also not possible. After the last configuration is completed, the optimisation model loop ends.

The results of the loop are a list of possible configurations of the network. The list of results is sorted in order of the least expensive to the most expensive solution. The least expensive solution is then obtainable from the optimisation model. The solution is the two furnaces' gas mixtures required to achieve the lowest possible cost of the network. The gas mixtures can then be used in the furnace energy consumption models to simulate the furnaces' required gas flows.

The optimisation model can be developed using any programming language and system as available or required. In this study, the Python programming language has been chosen for determining the optimal solution of a network. The next section combines this section's optimisation model, the previous energy models and the network configuration setups in a system that can be used in real-time by a system operator.

3.4 Real-time gas distribution optimisation system

3.4.1 SYSTEM REQUIREMENTS

This section uses all the tools developed in the chapter and combines them into a system that can be used to optimise the gas distribution network. A network of furnaces is modelled using the furnace energy characterisation models of Section 3.2. The models are used to simulate the energy distribution of the network. The gas distribution can be optimised using the technique developed in Section 3.3.

An operator is responsible for managing the gas distribution to the plant. There are numerous factors that influence the daily operation of the plant. These factors, discussed in Section 3.3, influence the availability of gas. Plants can produce by-product gas and supplement a gas shortage with a purchased gas. In a network of multiple gas consumers of differing energy efficiencies, there is an opportunity to optimise the distribution of gas.

An operator must take many factors into consideration when moving gas between different consumers. It is possible to distribute the plant gases in a way that is not optimum for minimum energy consumption due to these considerations. A system designed to assist the operator in decision making must give clear instructions. These instructions should be easy to read and be based on actual information available from control systems.

Real-time information reading into the system will be beneficial for quick decision making. The system should have a direct connection to control system information. The operator must also be able to input a change in the amount of by-product gas. This is necessary because a change in the system can be decided upon before it can be seen by the system. Allowing the operator to adjust the amount of gas in the system will simplify the decision-making process in fuel switching. The system can be adjusted and optimised by the system, giving the operator an instruction before a potentially wrong decision is made.

3.4.2 SYSTEM LAYOUT

A real-time optimisation system requires clear outputs of instructions to be beneficial to a gas network operator. To this end the design of such a system is important. A few required objects of system components can be seen in Figure 3-10, Figure 3-11 and Table 3-1. These components will be present in the creation and design of an optimisation system. The objects provide easy to understand information regarding the network gas distribution.

The information displayed in Figure 3-10 is the current distribution of gas to various furnaces. The number of furnaces can be adjusted according to the network layout. The values displayed in the figure are the input values of the optimisation model. The percentage distribution is the split of energy to each furnace.

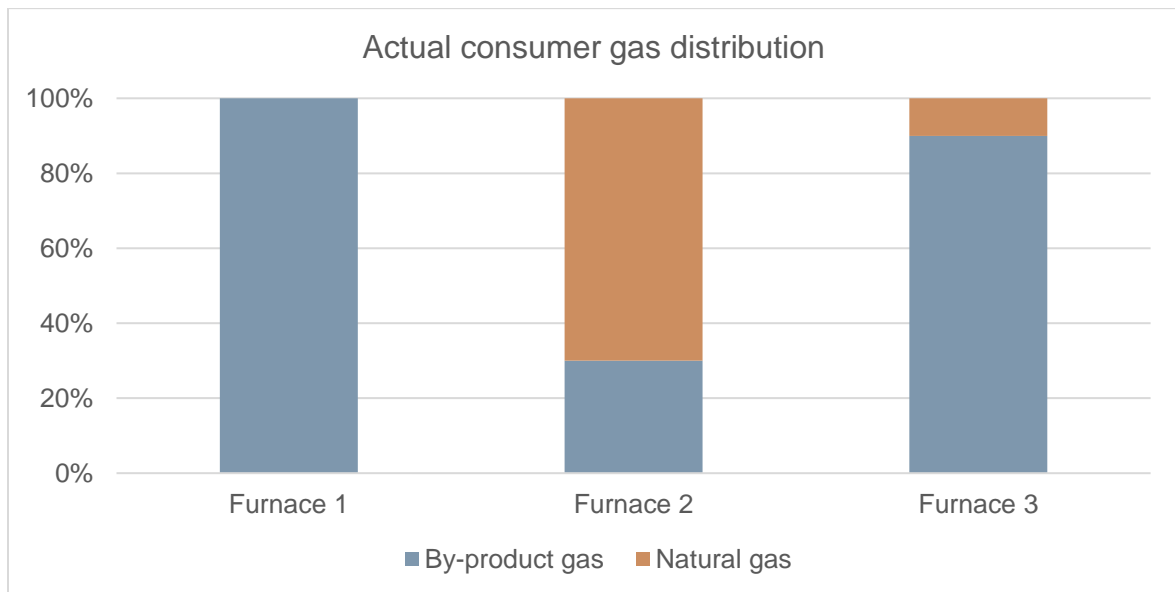


Figure 3-10: Actual network gas distribution and mixtures

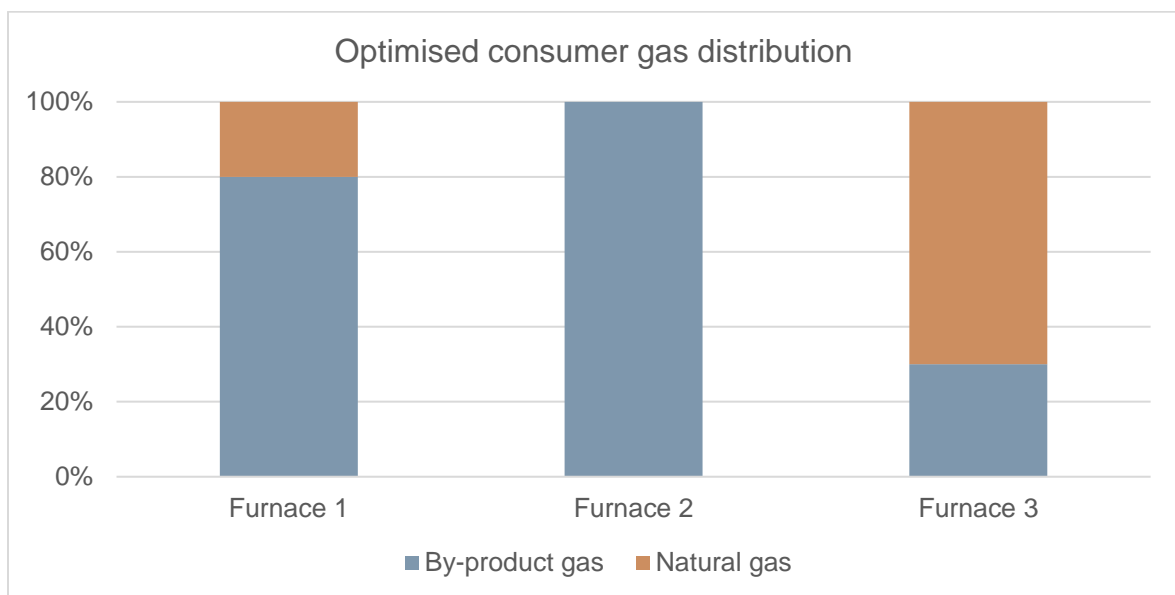


Figure 3-11: Suggested network gas distribution and mixtures

Table 3-1: Actual and suggested gas flow distribution changes

GAS		FURNACE 1	FURNACE 2	FURNACE 3
		m ³ /h	m ³ /h	m ³ /h
Actual	By-product gas	9000	2000	800
	Natural gas	0	4000	0
Change	By-product gas	-3300	4100	-600
	Natural gas	1800	-4000	300

Figure 3-11 shows the results of the optimisation of the gas network in the same format as the previous figure. This gives a visual indication of what action is necessary to ensure that the system is run optimally. If the amount of by-product gas in the system stays constant, it can indicate that the system is not operated at the most efficient point. If the amount of gas is changed in the system as an input to the optimisation model, it can be used to make decisions before the system needs to be changed.

In Table 3-1 the detail results of the optimisation are shown to the operator. The two different gases used in the system and the distribution of the various furnaces is shown. The actual gas consumption flow [m^3/h] and gas distribution of each furnace are displayed in the first two rows. The required changes needed to distribute the gas optimally is shown in the next rows. Detail values are shown to the operator so that exact changes can be made to the system if the operating parameters require it.

The example in the figures and table indicate the gas distribution of three furnaces. The optimisation requires a reduction in furnace 1 and 3's by-product gas consumption. The gas must be redistributed to furnace 2 for optimal gas consumption in the system. The result of this change will have a reduction in natural gas as an effect.

3.5 Optimisation system benefit quantification method

3.5.1 BENEFIT OF SYSTEM USE

The benefit of the system use should be determined before the system is implemented on the plant. The scope is to determine the energy saving opportunity for optimisation of the plants gas distribution. Historical by-product and natural gas flow to all the plant furnaces are required for this. The period selected for the benefit identification should reflect as many plant operational configurations as possible. The by-product and natural gas flow to the plants will be used to determine if there is an opportunity for gas distribution optimisation.

The historical gas flows to the plant furnaces must be used to develop and calibrate the plant's furnace characteristics models as set out in the previous sections. Using these models, the historical data can be run through the optimisation algorithm. The result of this backtest will indicate what the optimisation benefit would have been if the algorithm was used in the period. It should be used to determine if there is scope for the implementation of the system to optimise the gas distribution on the plant.

3.5.2 BASELINE DEVELOPMENT

A baseline represents what the gas consumption of the plant would have been without any energy saving intervention. It is necessary to quantify several system parameters to develop the baseline and calculate the benefit of the system use. The most important of these parameters is a by-product and natural gas consumption for all the furnaces within the system boundary of the baseline.

The solution of the optimisation system developed in Section 3.3 will always provide the least expensive gas distribution. The difference in gas consumption between the actual plant consumption and the optimisation algorithm's suggested consumption will indicate the system benefit. The optimisation algorithm will be used to identify the lost opportunity or system benefit during the baseline period. The resulting data of the algorithm is grouped with different groupings to create a baseline model.

3.5.3 BASELINE MODEL

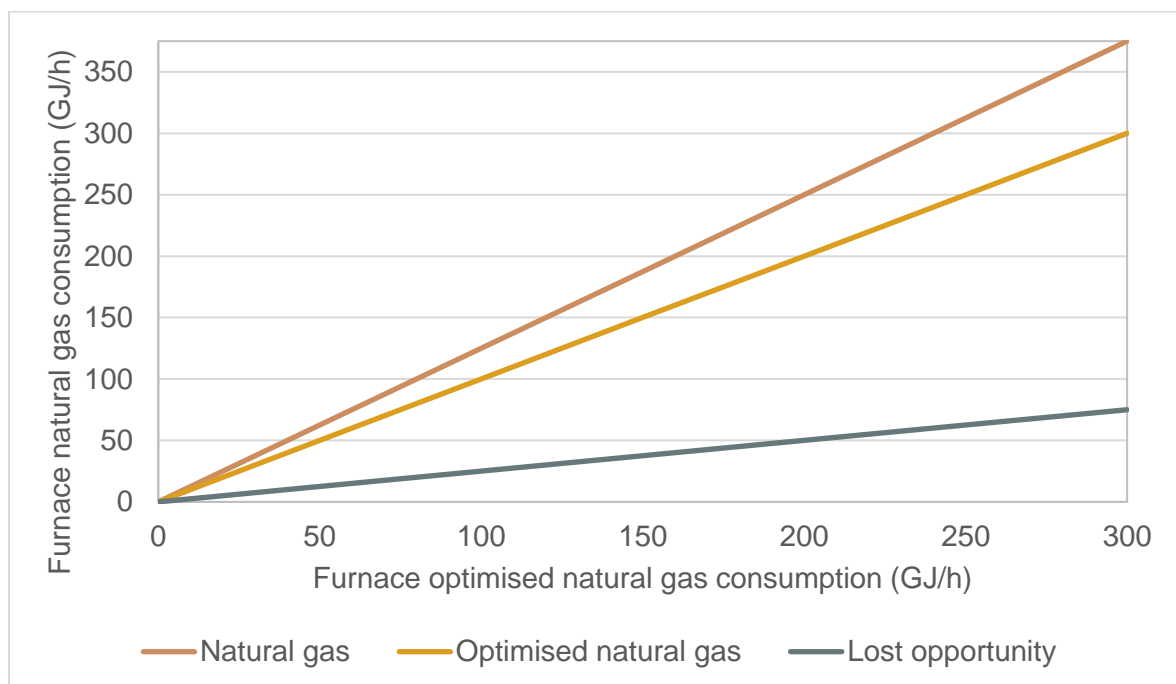


Figure 3-12: Example of the optimised average natural gas consumption for a gas network

The data for natural and by-product gas consumption for each mill furnace is run through the optimisation system to obtain the lost opportunity compared to the previous natural gas distribution that occurred. The data used is the actual furnace by-product and natural gas consumption, optimised natural gas consumption and the difference as a lost opportunity.

The data is arranged in increasing optimised natural gas consumption order. Figure 3-12 shows an example of the average natural gas and optimised natural gas consumption in GJ/h for a gas distribution network. The lost opportunity for the network is then calculated.

The mills are grouped according to furnace workload as used in the optimisation system as well as the total natural gas going to the mills. A furnace load of less than 30% is assumed to indicate idling, low or no production in the furnace. A load of more than 30% is assumed to indicate that the furnace is in production. Table 3-2 shows an example of the possible operational configurations of two furnaces.

Table 3-2: Example of the gas network configurations of two furnaces

STATUS #	FURNACE 1	FURNACE 2
1	Off	Off
2	Off	On
3	On	Off
4	On	On

Further grouping is done on the total natural gas consumed by the furnaces every hour in GJ. The grouped values include the lost opportunity calculated per hour in GJ natural gas to the furnaces. The result is a summarised table of the lost opportunity in the natural gas distribution to each furnace for varying natural gas consumptions. Table 3-3 shows an example of the grouped lost opportunity figures for the network of two furnaces in Table 3-2. The lost opportunity values are grouped in increments of natural gas to the furnaces in GJ/h.

Table 3-3: Example of the grouped natural gas lost opportunity of a furnace network

STATUS #	NATURAL GAS TO THE FURNACES [GJ/H]		
Low	0	100	200
High	100	200	300
1	10	20	25
2	15	40	20
3	25	20	30
4	25	25	20

The summary table provides an indication of the previous behaviour of the gas network operators. A comparison can be made between the previous control philosophy and the improved system provided in this study.

3.5.4 QUANTIFICATION OF SYSTEM BENEFIT

The baseline model will be used to quantify the achieved gas consumption savings on an hourly basis. The post-implementation by-product and natural gas consumption of the mills will also be run through the optimisation system. The difference in natural gas lost opportunity will be the resulting saving or system benefit.

The optimised natural gas consumption will be used to find a comparable scenario in the baseline period in the summarised table. Equation 3-4 is used to calculate the hourly natural gas savings. Where the hourly energy benefit (E), is the difference between the baseline and actual optimised energy consumption in GJ.

$$E_{Benefit} = E_{Baseline} - E_{Actual} \quad 3-4$$

The cost benefit is calculated by multiplying the hourly energy saving benefit from Equation 3-4 with the natural gas cost rate, as billed by the plant. If no optimisation is achieved during the assessment period, the energy savings will be taken as zero.

Because the performance will be assessed every hour, there are multiple time periods where no optimisation is possible. These periods will be identified based on the following criteria:

- The total gas distribution to the mills is higher than 95% natural gas;
- The total gas distribution to the mills is lower than 5% natural gas;
- When the measured gas consumption values to the furnaces are 20% higher than the determined furnace possible maximum load. This is in cases where the plant measurements are incorrect or out of range;
- When no optimisation result is returned from the optimisation model; and
- If no precedent can be found in the summary table for the baseline period, no performance will be calculated.

3.6 Summary

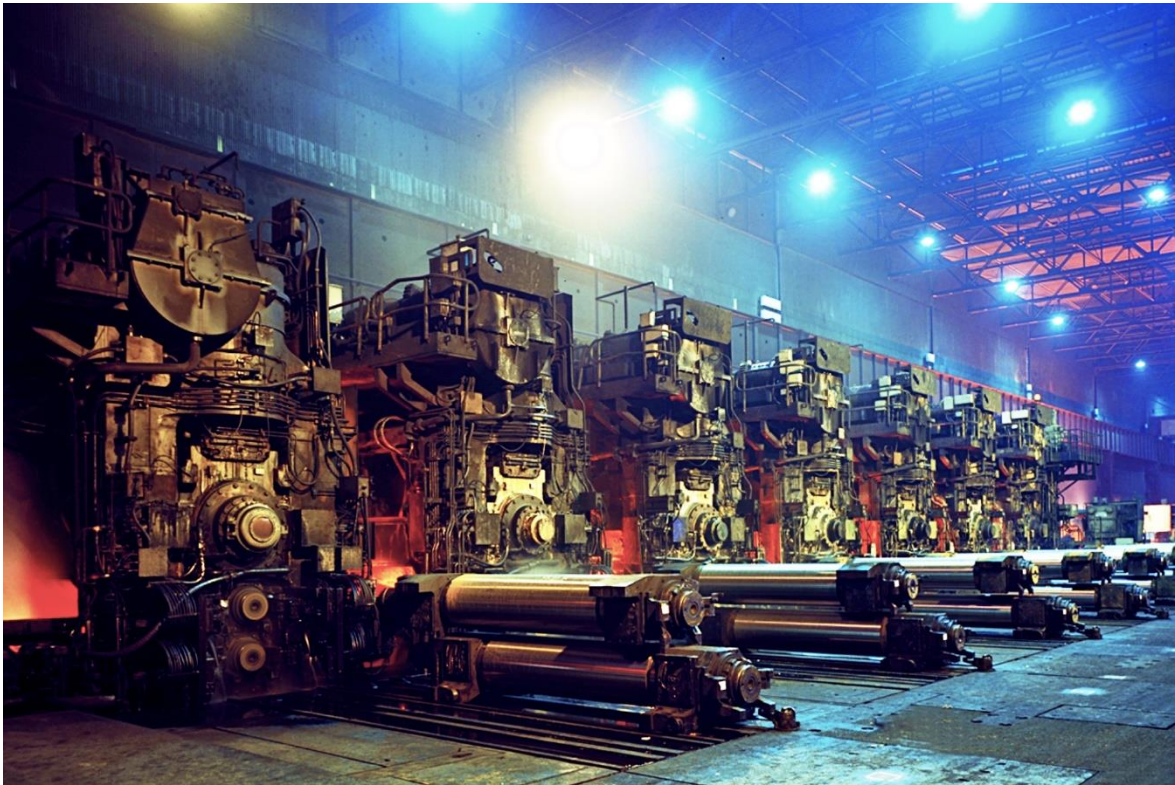
An optimisation methodology was developed in this chapter. The furnace behaviour was studied to develop furnace energy characterisation models. These models were developed from typical reheating furnace measurements. They can provide insight into the furnace energy consumption under different operational characteristics. They can also simulate the furnace energy consumption for these conditions. An experimental verification procedure was also developed.

The models were configured in a gas distribution network. They can be used to simulate the energy consumption of the entire furnace network. The simulation encompasses each individual furnace's operational characteristics. The simulation was then run through an optimisation algorithm to return the lowest possible furnace natural gas distribution.

The algorithm together with the furnace characterisation models was used to develop the scope of a system that can be used by a steel production facility. The result was a real-time optimisation system that can be used by the gas distribution network operators to assist in improved decision making regarding furnace natural gas consumption.

Finally, a method was developed to quantify the benefit of the optimisation system. This consisted of the development of a baseline for the previous natural gas consumption of the network. This baseline can then be used to determine the impact of the implementation of the real-time optimisation system.

4 VALIDATION THROUGH CASE STUDY



Steel finishing mills. ⁷

⁷ Siemens, *Siemens to modernize main drives in two hot rolling mills of ArcelorMittal in Europe*, 2012 [Online]. Available: <https://www.siemens.com/press/photo/IMT201205461-01e>. [Accessed 8 October 2017]

4.1 Preamble

In this chapter, the methodology that has been developed in the previous section is validated on a case study for which background is provided. The methodology requires that the furnaces in the system be characterised and modelled. These models are used to develop an optimisation model. The optimisation model is then backtested on historical data to determine the benefit of implementing the model. A real-time optimisation system is developed and implemented for a period to verify the system and the system benefits are then calculated and briefly discussed.

4.2 Case study information

4.2.1 BACKGROUND

A case study has been selected to validate the methodology developed in the previous chapter. The plant is a steel producer based in South Africa. It produces profile products in various steel grades for local and international markets.

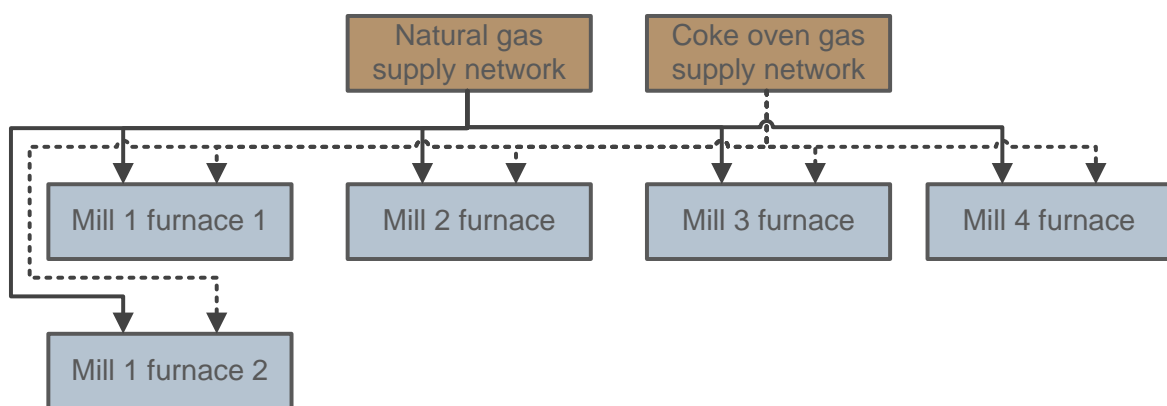


Figure 4-1: Plant layout of case study

The plant layout is shown in Figure 4-1. The plant has coke oven batteries that produce Coke Oven Gas (COG) as a by-product. The gas is cleaned and then distributed through a gas network. The network consists of a pipe network for the by-product gas and pressure controlling components. The pressure is controlled by use of gasholders and flare stacks. When the gasholders level or the pressure in the system is too high, gas is burned off in the flare stack. This is a loss of energy as the gas could have been used for other purposes.

The supply distribution of COG to its consumers is determined and controlled by a human operator. The operator is responsible for distributing the gas to the various consumers across the works. The consumers vary in their demand for gas throughout the day. It is a complex task to balance all the consumers and fuel gases in the distribution network. The operator cannot always find the most optimum solution in the system and human error causes losses in gas consumption.

The distribution system is not automated and the operator is responsible for deciding where to distribute the gas. Between all the consumers there may be more efficient solutions at any given time and this complicates the operator's task. The operator must phone the different plants' operators to change the consumption distribution of gas.

The COG in the system is consumed by various plants throughout the works. It is very important that the available COG in the system is utilised optimally. Any shortfall in COG supply is supplemented with natural gas that is purchased as an additional fuel source. This is an unnecessary extra expense for the plant as the available COG could have been redistributed to a more efficient consumer.

The plant has four mills that produce different steel products. The mills have five reheating furnaces between them, with mill 1 having two furnaces. The furnaces are designed to operate on COG, but a gas shortage in the network can be supplemented with natural gas that can be supplied to each furnace. There are different furnace types in each plant.

4.2.2 MILL AND FURNACE DESCRIPTIONS

Mill 1

Mill 1 is the first mill in the process that processes steel blooms received from a continuous caster into billets and round bars for the secondary mills (mill 1, 2 and 3). Two 150 tonne per hour pusher type furnaces reheat the blooms. The gas used in these furnaces (shown in Figure 4-2) is mainly COG or a combination of COG and natural gas.

A reversing mill is used to shape the blooms into blooms for dispatch, or for the continuous mill, where two vertical and two horizontal stands are used for further rolling into billets or round bars, after which a flying shear cuts the products to length.



Figure 4-2: Mill 1 reheating furnaces

Mill 2

Mill 2 has three sections: the mill area, finishing area and the roll preparation area. The products rolled in this mill comprise of rounds, billets, flats, rails, beams, channels, equal leg angles, unequal leg angles and other special profiles. Various sizes of each profile are rolled. The mill can produce a total of nearly 500 products. Production varies between 30 000 and 50 000 tonnes per month depending on the product mix.

The mill consists of a walking beam reheating furnace (shown in Figure 4-3), two reversing mill stands, six horizontal and three vertical/horizontal mills. The material is cut into cooling bed lengths. From the cooling bed, the material goes through straighteners into a finishing area where the material is cut to length then piled, bundled and dispatched.



Figure 4-3: Mill 2 reheating furnace

Mill 3

Mill 3 uses different mill set-ups or paths to roll reheated intermediate billets into finished profile products. Final products are produced from billets that are reheated in the furnace in Figure 4-4 and passed through the eight-stand roughing train, where the billet cross-section is reduced. Further reduction and profiling take place through the five-stand intermediate trains and the four-stand finishing train.

The final products are angles, flat bars, squares, round bars and some special sections. The products are either coiled or run out onto the cooling beds as a straight bar. These are cut into lengths and bundled before being dispatched.

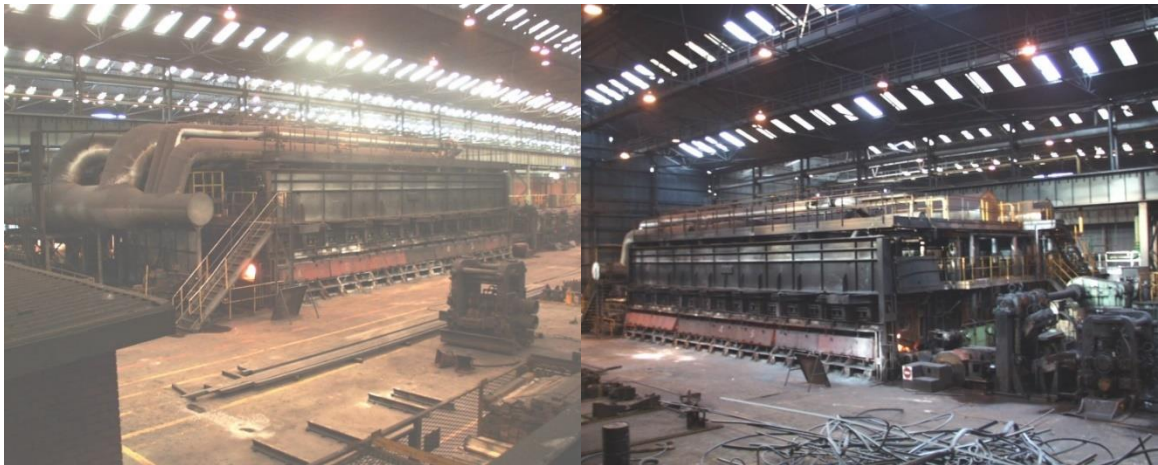


Figure 4-4: Mill 3 reheating furnace

Mill 4

This mill produces rods in varying sizes in various steel grades ranging from low carbon steel to high carbon and alloy steel. The plant has a pusher type reheating furnace shown in Figure 4-5. The plant has a seven-stand roughing mill, an eight-stand intermediate mill and a ten-stand finishing mill. The reducing block allows rolling speeds of up to 100 meters per second on smaller diameter rods. The finished product is coiled, compacted and tied with steel straps before dispatch. The rods are used in the manufacture of steel ropes, bolts and nuts, welding wire, fencing wire, steel wool, etc.



Figure 4-5: Mill 4 reheating furnace

4.2.3 MILLS FURNACE PRODUCTION AND ENERGY REQUIREMENTS

The plant production output figures for 2016 for each mill is shown in Figure 4-6. Mill 1 produced 1 140 kilotonne [kt], mill 2 produced 281 kt, mill 3 produced 297 kt and mill 4 produced 594 kt respectively. The plant did not reach its maximum production output in 2016 due to low market demand for steel. The last quarter of 2016 had especially low production figures. The production breakdown for the mills can be found in Appendix A.

The plant experienced additional difficulties to the low market demand throughout. Breakdowns at the coke plant had the result of lower COG production and availability at the mills. Natural gas had to be supplemented throughout the year, with the largest requirement from April to September 2016.

The mills' gas consumption for 2016 is shown in Figure 4-7. The lower COG availability can be seen from April to September 2016. Total gas consumption for the mills for 2016 was 1 462 000 terajoules [TJ] natural gas and 2 423 000 TJ COG. Natural gas is purchased as an additional energy source and this has significant cost implications for the plant.

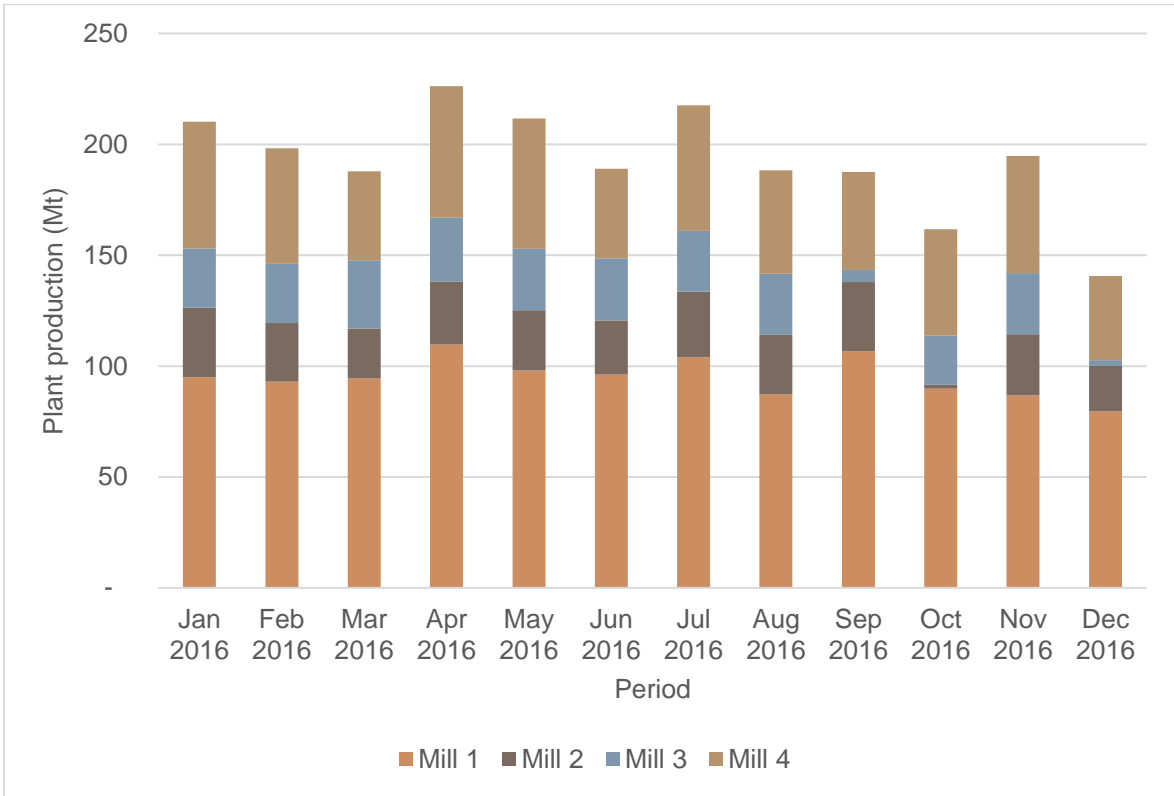


Figure 4-6: Plant production output for 2016

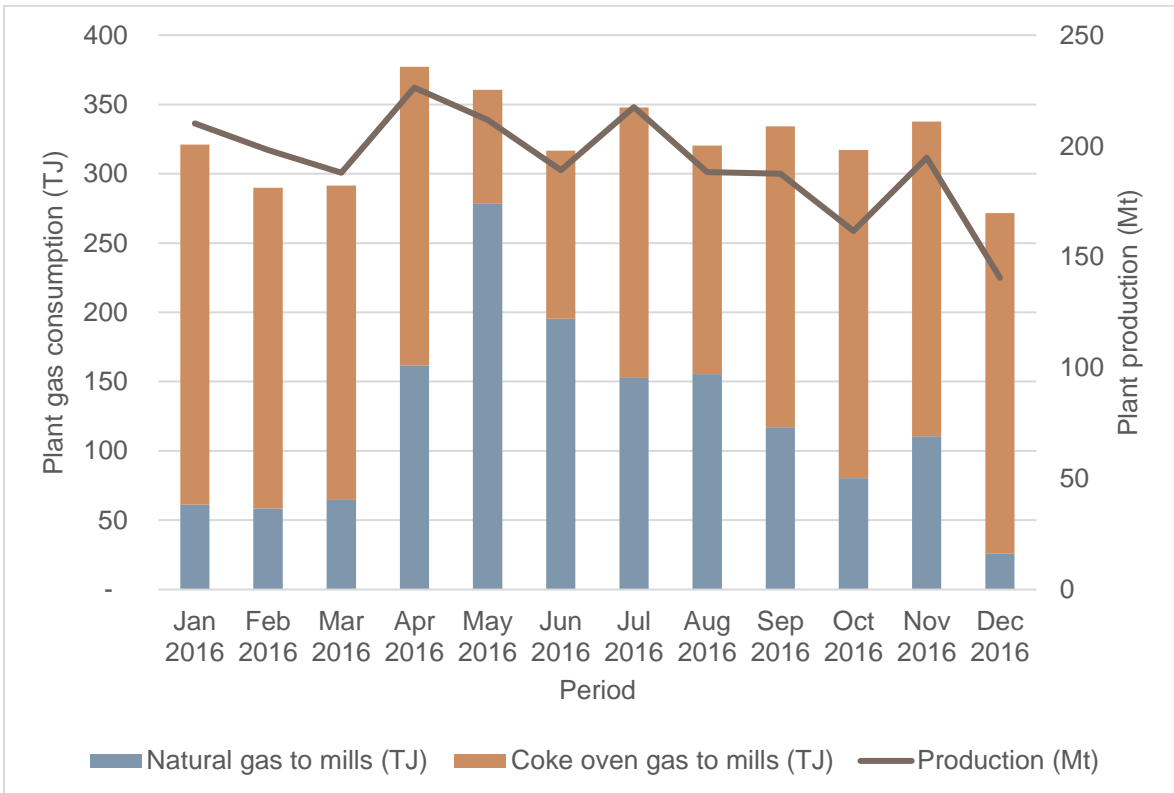


Figure 4-7: Mill gas consumption figures for 2016

4.2.4 FURNACE ENERGY MEASUREMENTS

The plants' reheating furnaces are large consumers of gas in the works. It is therefore measured extensively. Each furnace has burners located in different regions found in the furnace. The different zones in the plant furnaces are indicated in Table 4-1. Each zone is outfitted with flow measurement instruments for each gas type that measures gas in cubic meters per hour [m³/h]. The total fuel consumption for each furnace is aggregated for each gas type.

Throughout the furnace lifetime, some of the zones have been changed to operate on different gases or removed entirely. It can be seen in Table 4-1 that the preheat zones of the furnaces at mill 2 and 3 have been disabled entirely. The throughput of the furnace is low enough to support this reduction in heat supply. The furnace at mill 4's preheat zone has been modified to only operate on COG.

Table 4-1: Plant furnace zones and fuel types

FURNACES	ZONES	FUEL TYPES
Mill 1 furnace 1 & 2	Preheat zone	Natural gas & coke oven gas
	Bottom heat zone	Natural gas & coke oven gas
	Top heat zone	Natural gas & coke oven gas
	East soak zone	Natural gas & coke oven gas
	West soak zone	Natural gas & coke oven gas
Mill 2 furnace	Preheat zone	Disabled
	Lower heat zone	Natural gas & coke oven gas
	Upper heat zone	Natural gas & coke oven gas
	Lower soak zone	Natural gas & coke oven gas
	Right upper soak zone	Natural gas & coke oven gas
Mill 3 furnace	Left upper soak zone	Natural gas & coke oven gas
	Preheat zone	Disabled
	Heat zone	Natural gas & coke oven gas
	East soak zone	Natural gas & coke oven gas
	Centre soak zone	Natural gas & coke oven gas
Mill 4 furnace	West soak zone	Natural gas & coke oven gas
	Preheat zone	Coke oven gas
	Heat zone	Natural gas & coke oven gas
	East soak zone	Natural gas & coke oven gas
	Centre soak zone	Natural gas & coke oven gas
	West soak zone	Natural gas & coke oven gas

4.3 Implementation of furnace characterisation models

4.3.1 DEVELOPING FURNACE CHARACTERISATION MODELS

The method set out in Section 3.2 was followed to develop the furnace characterisation models. Data was collected from each furnace from April 2016 to January 2017. The data was the total flow of each gas to the furnace measured in m³/h. The flow values were converted to energy [GJ] using the plant gas energy constants shown in Table 4-2.

Table 4-2: Plant fuel gas energy constants

GAS	ENERGY CONSTANT
	GJ/m ³
Natural gas	0.036
Coke oven gas	0.017

The methodology was followed to characterise each furnace in the gas network. Characterisation models for the plant furnaces were developed using the natural gas and COG flow data to each furnace. The data was grouped by the mixture of COG to natural gas in the gas to the furnace. The hourly total gas consumption to the furnace was then plotted for each furnace. The result for each furnace can be seen in Figure 4-8, Figure 4-9, Figure 4-10, Figure 4-11 and Figure 4-12.

A regression line for each furnace was developed using the highest energy flow values achieved by the furnace. From these values, the 10% highest and lowest gas flow mixtures to the furnace were selected. Finally, the selected values were filtered to only include the ten highest values in each group. The remaining values were used to develop the characterisation model for each furnace. The selected values are marked in the figures mentioned previously.

A clear maximum energy flow can be seen in each furnace. The selected values were used to develop a regression line that was used to simulate the maximum energy consumption of each furnace. The regression lines are also indicated in each figure indicating the characterisation models. A regression line formula was used to simulate the gas energy consumption values.

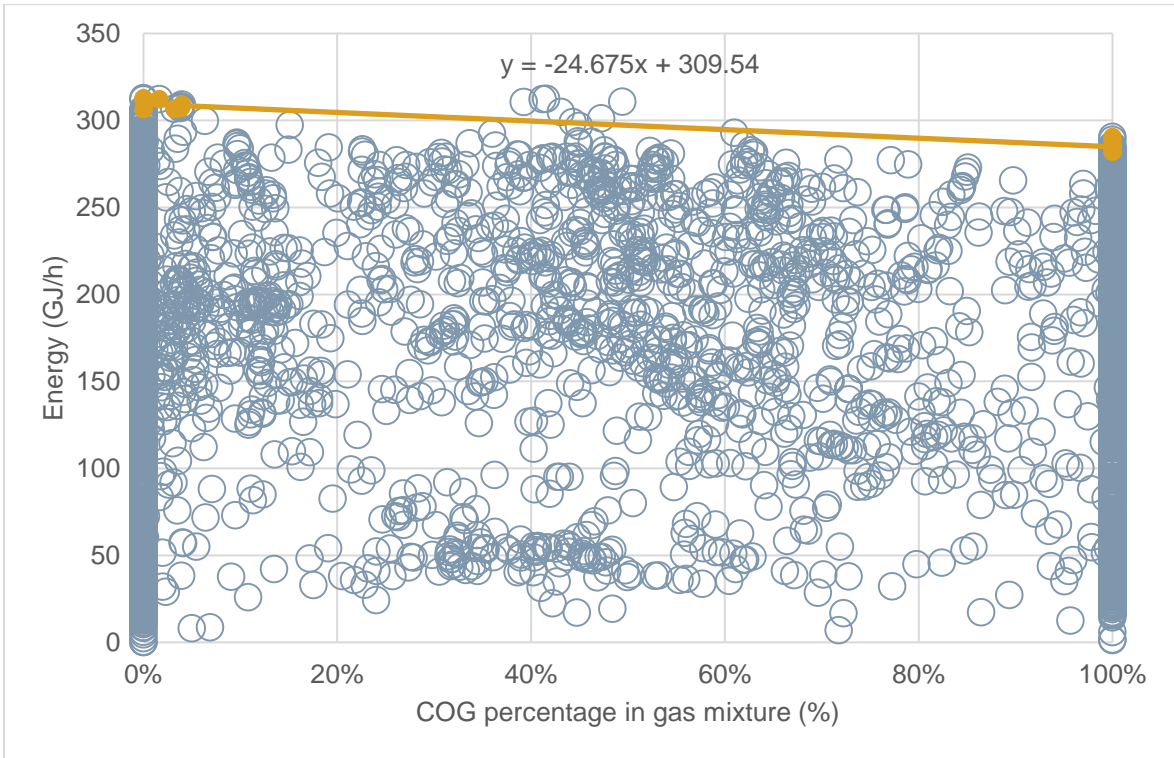


Figure 4-8: Mill 1 furnace 1 energy per hour characterisation model

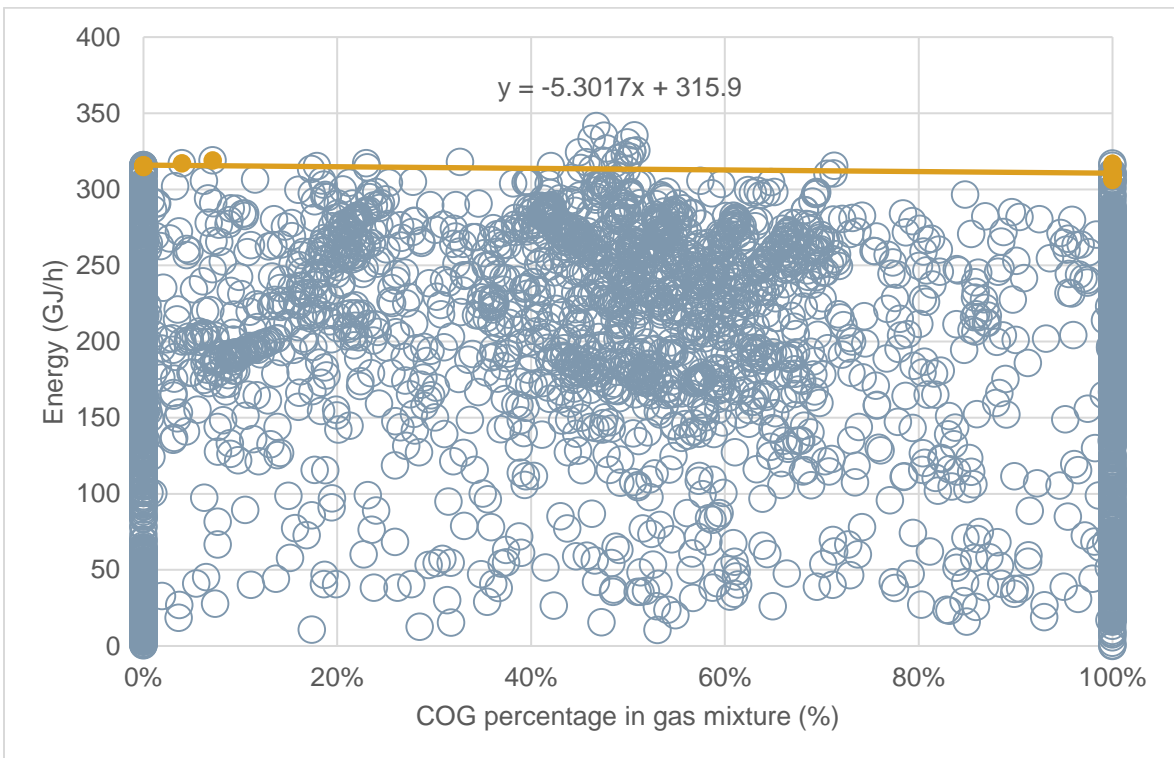


Figure 4-9: Mill 1 furnace 2 energy per hour characterisation model

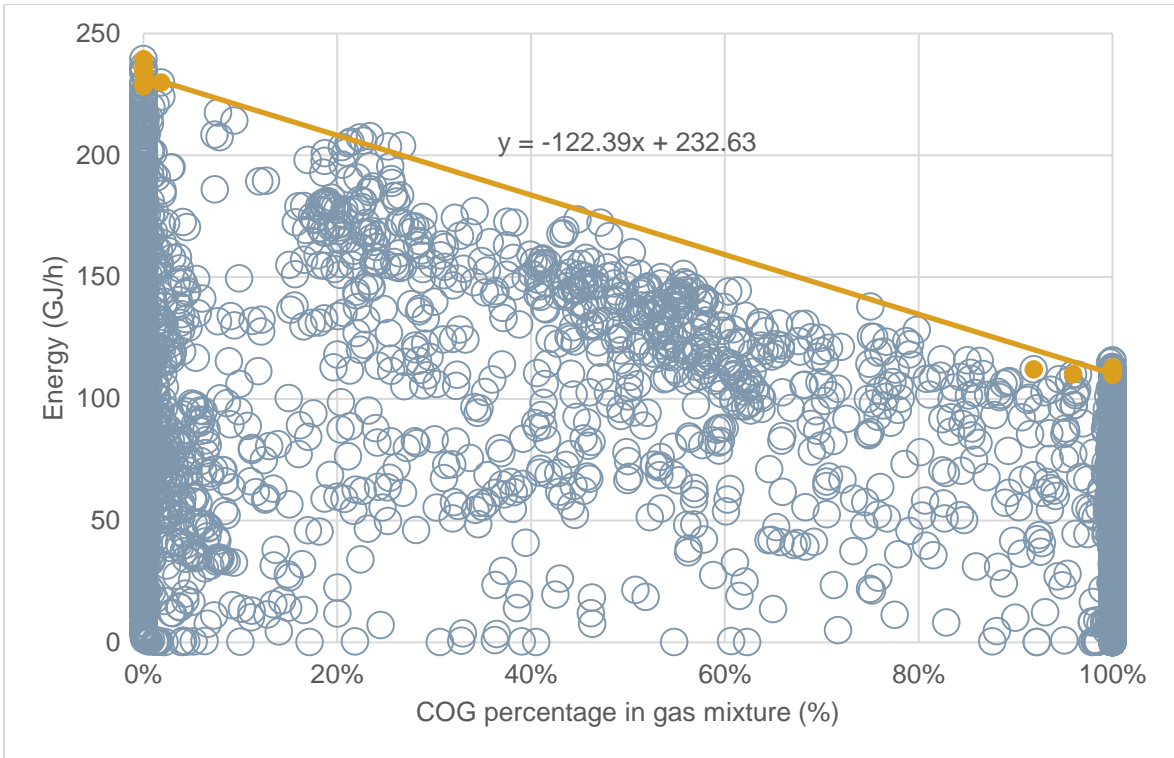


Figure 4-10: Mill 2 furnace energy per hour characterisation model

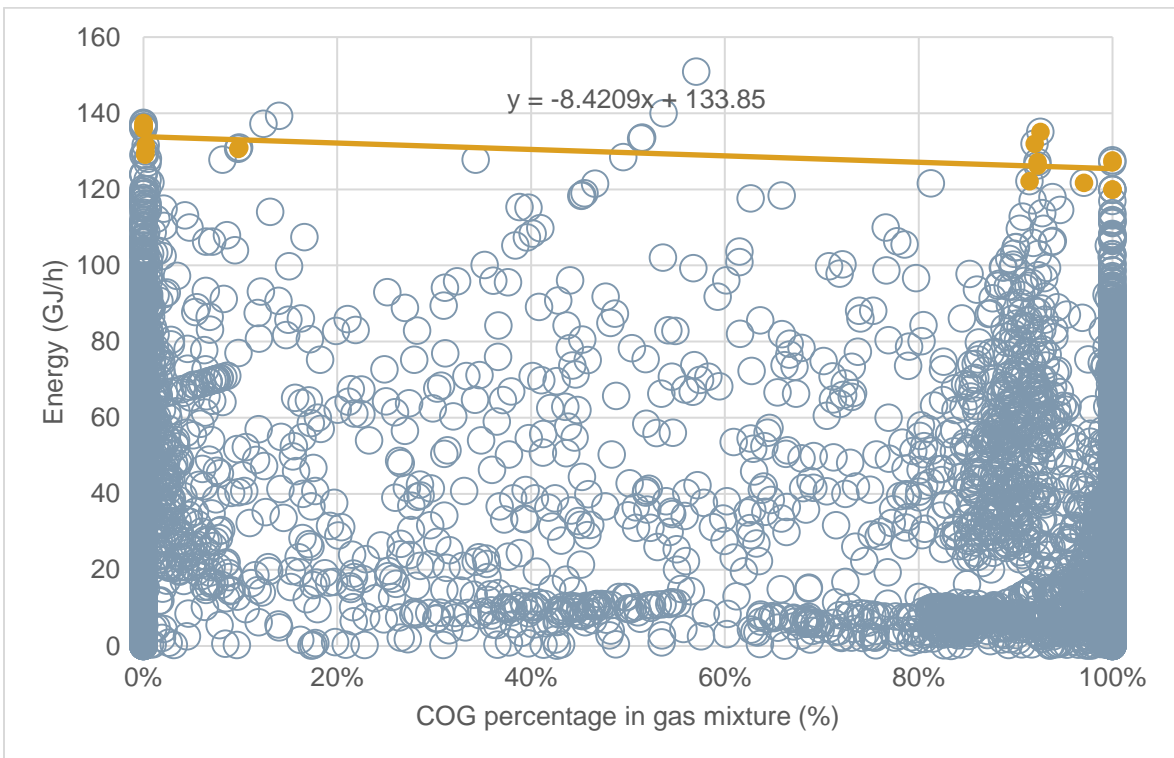


Figure 4-11: Mill 3 furnace energy per hour characterisation model

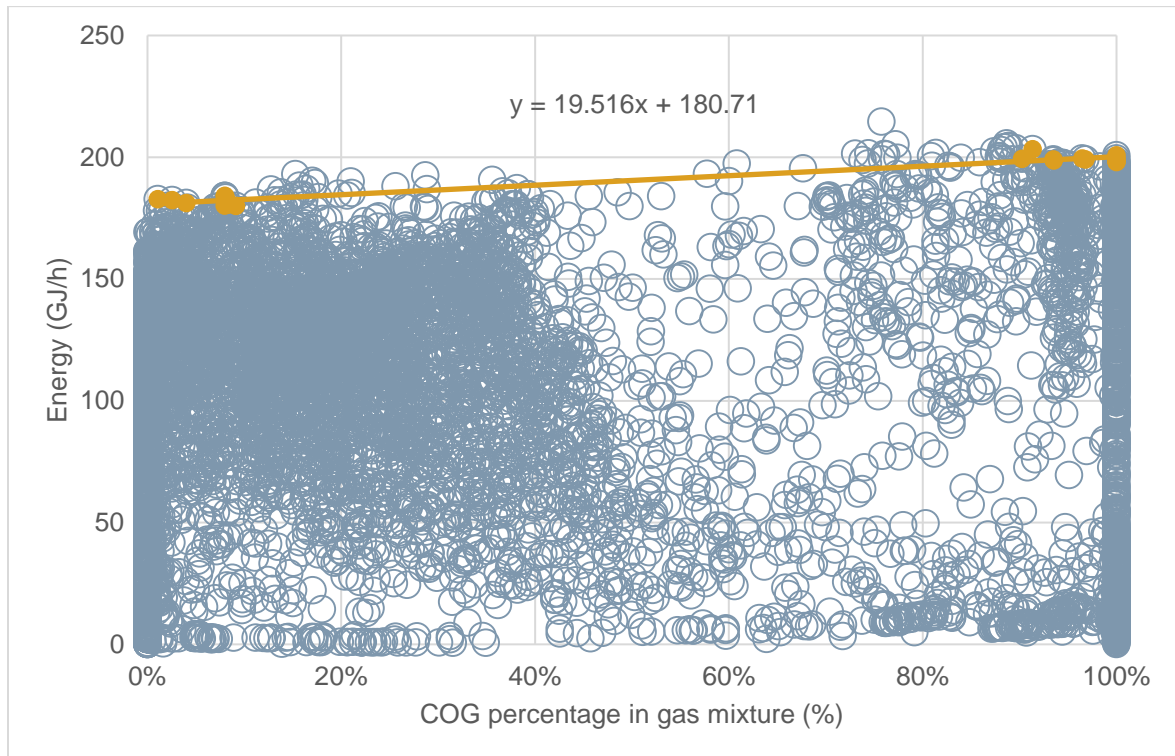


Figure 4-12: Mill 4 furnace energy per hour characterisation model

What was apparent from each furnace model was that each furnace has differing energy consumption characteristics. The furnaces were different in a few aspects. These aspects of the characterisation are:

- Maximum energy consumption;
- Energy consumption on different mixtures of COG and natural gas;
- Preference in furnace operation.

The two furnaces for mill 1 in Figure 4-8, Figure 4-9 were the largest on the plant. These furnaces were identical. However, their characteristics were different. Furnace 1 was more efficient in hourly energy consumption overall as can be seen from the C value of the regression line. Furnace 1 was also more efficient on COG than furnace 2 as can be seen from the slope of the regression lines. The difference in characteristics can be attributed to the age of the furnaces and different levels of maintenance.

The furnace from mill 2 indicated in Figure 4-10 was also a large energy consumer. The furnace was markedly more efficient on COG than it was on natural gas. This was, comparatively, the most expensive furnace to operate on natural gas. Despite this, the furnace was operated on natural gas as can be seen from the data.

The furnace at mill 3 is indicated in Figure 4-11. It was the smallest of the plants' furnaces. It was operated more efficiently on natural gas. This was due to changes to the furnace burners to achieve required temperatures on COG. Previously the furnace could not reach the set temperatures on COG alone.

The final furnace at mill 4 is shown in Figure 4-12. The furnace was operated more efficiently on natural gas than it was on COG. This can be attributed in part to the preheat zone that cannot be operated on natural gas as the burners have been changed in this way. This furnace was a good candidate to operate on natural gas when there was a shortage of COG in the works.

The furnace characterisation model regression lines are indicated in Table 4-3. The lines are also indicated on the furnace models in the previously discussed figures. The regression lines can be used to simulate the variation in COG to a furnace as has been discussed in Section 3.2 of the methodology. These models will be used in the optimisation of the gas distribution network.

Table 4-3: Furnace energy per hour characterisation regression models

MILL FURNACE	M	C
Mill 1 furnace 1	-24.68	309.54
Mill 1 furnace 2	-5.3017	315.9
Mill 2	-122.39	232.63
Mill 3	-8.42	133.85
Mill 4	19.52	180.71

4.3.2 FURNACE CHARACTERISATION MODEL VERIFICATION

The model verification procedure suggested in Section 3.2 was followed on the furnace for mill 3. Furnace characterisation tests were performed for a two-day period. The tests were performed from 18 to 19 January 2017. The furnace was producing a single steel profile for this period. The production rate was high for the specific steel profile which resulted in high gas consumption and a good test environment.

It must be noted that it was extremely difficult to isolate a furnace's energy consumption characteristics at a constant rate for any period. The plant experienced intermittent stoppages throughout the day and this made any test problematic.

As indicated at the start of this chapter, the furnace at mill 3 has four operational zones: the upper heat-zone (UHZ), lower heat-zone (LHZ), lower soak-zone (LSZ) and the left and right upper soak-zones (USZ R/L). The furnace energy performance was mapped for each possible gas configuration of these burners, 16 in total. The configurations for coke oven and natural gas is indicated in Table 4-4. The percentage of COG in the total gas mixture is also indicated and the different configurations are sorted accordingly.

Table 4-4: Mill 3 furnace burner configurations for verification

BURNER GAS USAGE				CONFIGURATION	
UHZ	LHZ	LSZ	USZ R/L	#	Mixture
Coke oven	Coke oven	Coke oven	Coke oven	1	100%
Coke oven	Coke oven	Coke oven	Natural	2	68%
Natural	Natural	Coke oven	Natural	3	57%
Coke oven	Coke oven	Natural	Coke oven	4	52%
Natural	Coke oven	Coke oven	Coke oven	5	48%
Coke oven	Natural	Coke oven	Coke oven	6	45%
Coke oven	Natural	Coke oven	Natural	7	43%
Natural	Coke oven	Coke oven	Natural	8	38%
Coke oven	Natural	Natural	Coke oven	9	32%
Natural	Natural	Coke oven	Coke oven	10	29%
Natural	Coke oven	Natural	Coke oven	11	26%
Natural	Coke oven	Natural	Natural	12	20%
Coke oven	Coke oven	Natural	Natural	13	12%
Coke oven	Natural	Natural	Natural	14	8%
Natural	Natural	Natural	Coke oven	15	7%
Natural	Natural	Natural	Natural	16	0%

The furnace was operated on each of these configurations for a period. This was done to map the maximum energy consumption of the furnace as was used in the simulation model. Only the highest furnace load was used for the test results. To achieve this, only the periods where the temperatures were higher than 1000°C in the upper heat zone were used. The filtered hourly temperatures for the test of each configuration is shown in Figure 4-13.

The results of the characterisation tests are shown in Figure 4-14. The hourly energy consumption in GJ/h for five-minute intervals are plotted over percentage COG in the total gas to the furnace. These values have also been filtered for temperature. The furnace energy characterisation model is plotted over the verification data. The model has also been adjusted to simulate the values for 40% and 85% furnace load.

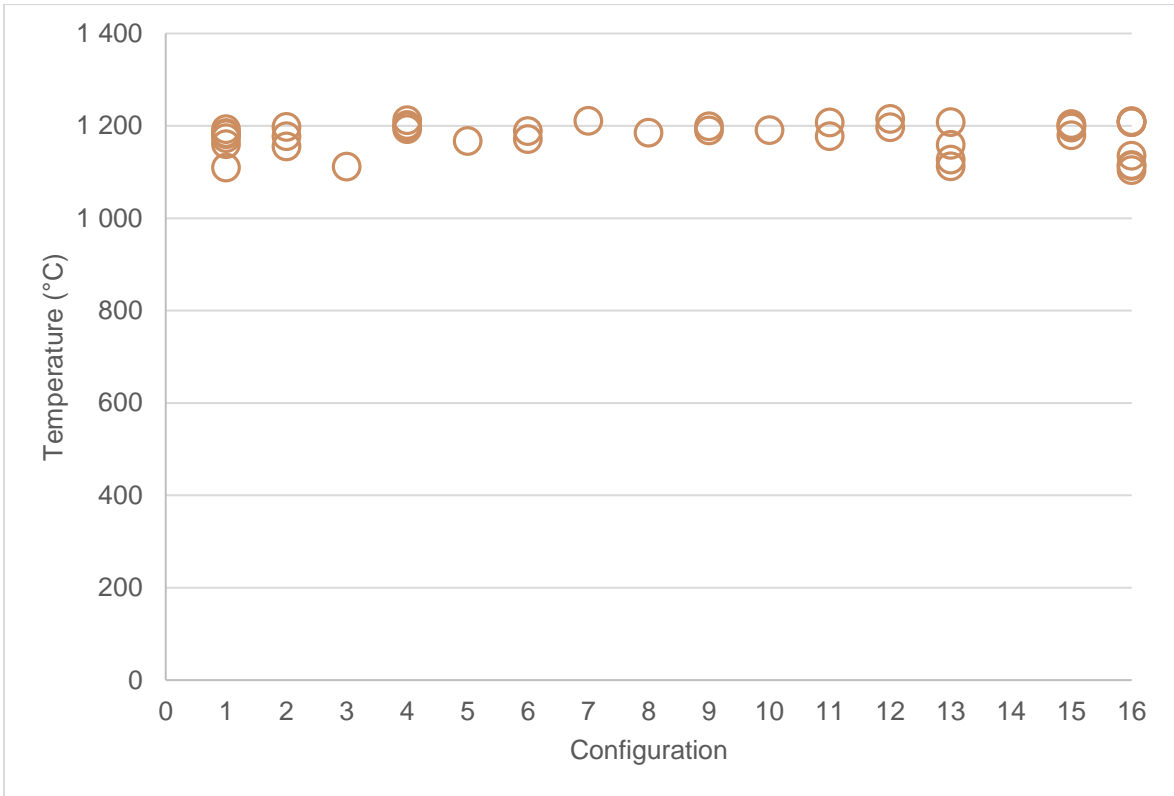


Figure 4-13: Mill 3 furnace characterisation model verification – Temperatures

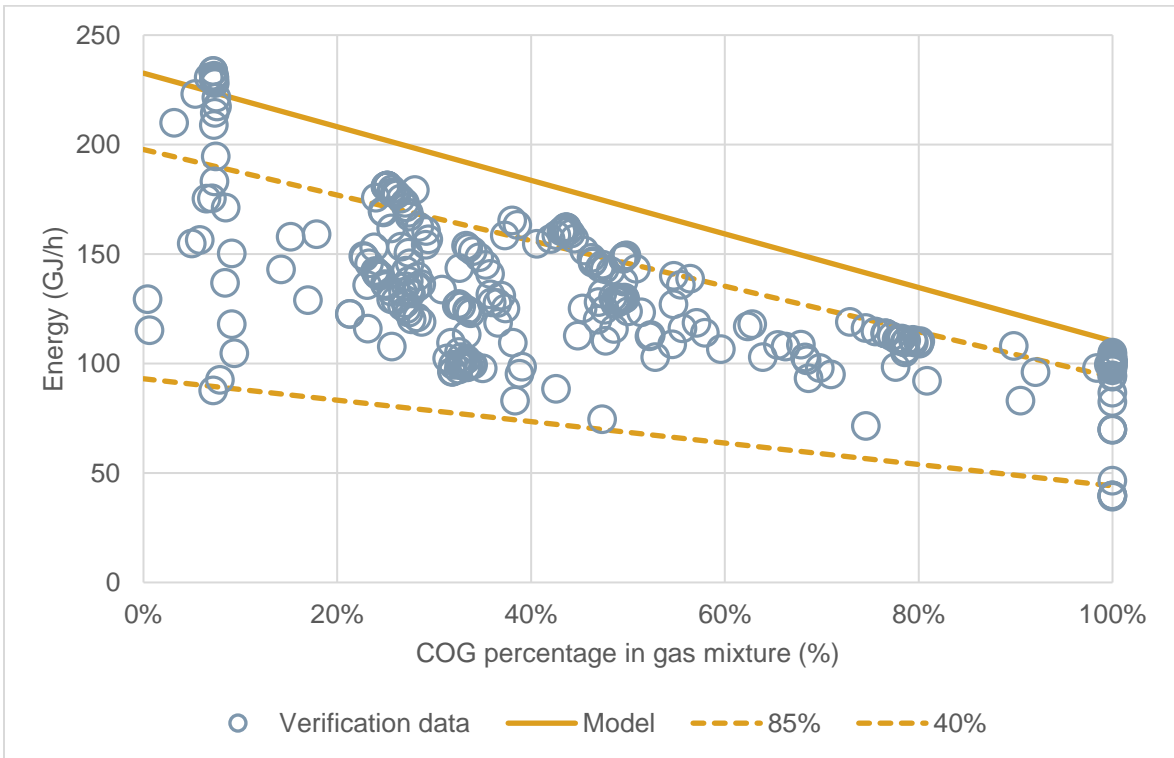


Figure 4-14: Mill 3 furnace characterisation model verification – 5-minute interval data

Even though the results were filtered for higher temperatures the energy consumption still varies considerably. The variation in temperature shown means that according to the furnace automated control, the burner will cut back when the zone was at the set temperature required. This was the cause of the varied energy consumption.

The tests show that there was a band on the graph where the furnace operates at high temperatures. A clear maximum energy consumption for the test period can be observed which was the required result of the tests. The verification was necessary to check whether the simulation can be used to simulate the furnace operation at another gas percentage mixture. The furnace was producing a single product at high temperatures for a nearly constant period. Thus, the characterisation model can be used to estimate furnace energy characteristics at different loads and percentage COG mixtures.

4.4 Application of the distribution optimisation model

The models generated in the previous section were used to develop an optimisation model for the plant. The optimisation model used flow data for each gas type to each furnace. Each instance of the data was then optimised for a total reduction in natural gas consumption for the plant gas network. This was done by using the furnace characterisation models developed in Section 3.2 and the optimisation model in Section 3.3.

The timeline of the data used for the development of the optimisation model was from April 2016 to January 2017. The gas flow consumptions for each furnace in hourly intervals were used in the optimisation model. The total coke oven and natural gas consumption for the plant can be seen in Figure 4-15.

An optimisation test was performed on historic data to calculate the opportunity for natural gas consumption savings. The optimisation model was used to optimise all the data points in this period. The goal of the optimisation was to solve the gas consumption of the system for reduced natural gas consumption. Each period was run through the optimisation model. The result was an optimised flow distribution of the available COG to the furnace based on their efficiency characteristics. The result of this was an overall reduced consumption of natural gas by the plant.

The results of the optimisation are also shown in Figure 4-15. The energy savings opportunity calculated by the optimisation model is indicated. Generally, there is reduced opportunity for optimisation when the amount of natural gas in the system increases.

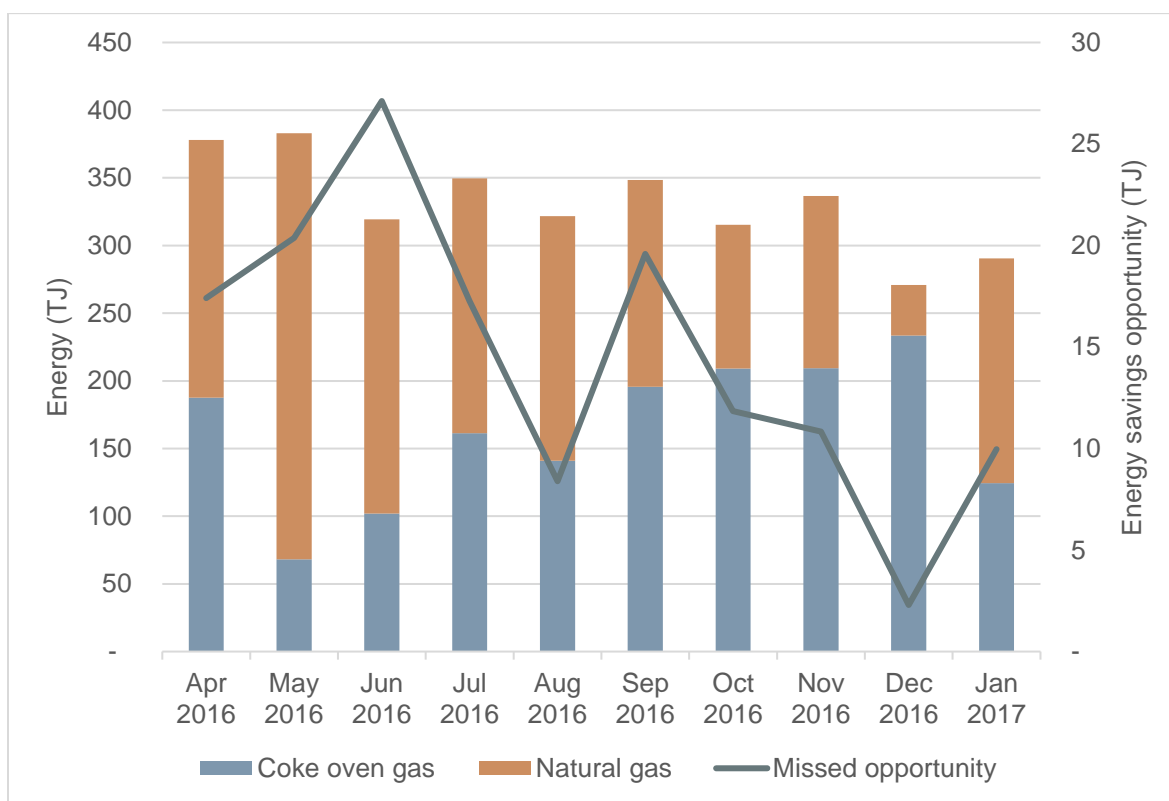


Figure 4-15: Plant energy consumption and optimisation results for the scoping period

The results of this backwards optimisation test indicated that there was a significant lost opportunity for natural gas consumption. The available COG could have been distributed in an optimal way. The gas could have been consumed by furnaces that were in operation and that were more efficient on natural gas. This would have resulted in an optimal use of COG and natural gas. Furthermore, it would have resulted in reduced operational costs for the works.

The results of the optimising process shown in Figure 4-15 is also indicated in Table 4-5. The total COG consumption for the period was 1.63 petajoules [PJ] where the total natural gas consumption was 1.68 PJ.

The optimisation model indicated a missed opportunity of 145 terajoules [TJ] for the project scoping period. This was a 9% loss in opportunity for saving on natural gas consumption. This indicated a significant opportunity for reduced consumption of natural gas.

Table 4-5: Plant energy consumption and optimisation results of the scoping period

MONTH	COKE OVEN GAS	NATURAL GAS	MISSED OPPORTUNITY	
	GJ	GJ	GJ	%
Apr 2016	187 536	190 526	17 415	9%
May 2016	68 121	314 943	20 370	6%
Jun 2016	101 910	217 312	27 116	12%
Jul 2016	161 370	188 246	17 267	9%
Aug 2016	141 033	180 606	8 385	5%
Sep 2016	195 648	152 664	19 583	13%
Oct 2016	209 171	106 198	11 837	11%
Nov 2016	209 332	127 360	10 836	9%
Dec 2016	233 503	37 368	2 296	6%
Jan 2017	124 502	165 875	9 964	6%
Total	1 632 127	1 681 098	145 069	9%

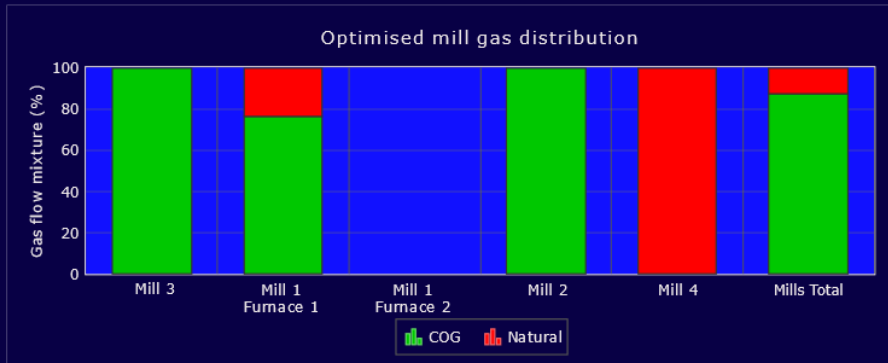
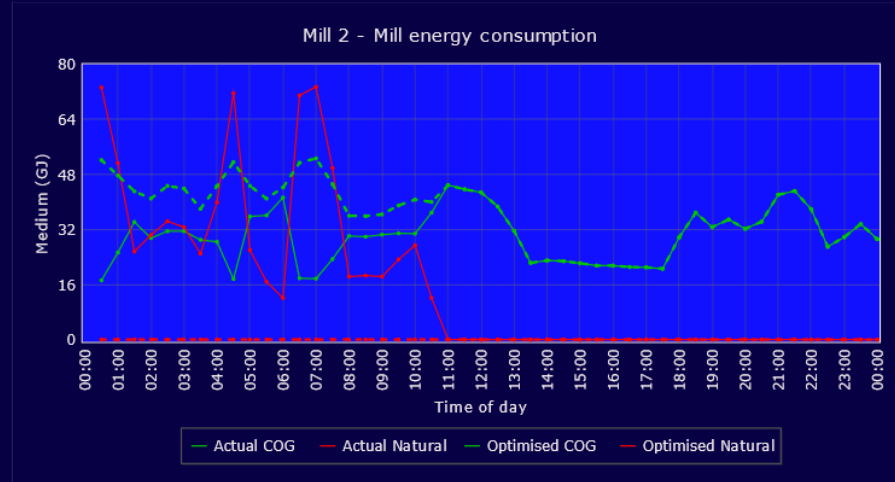
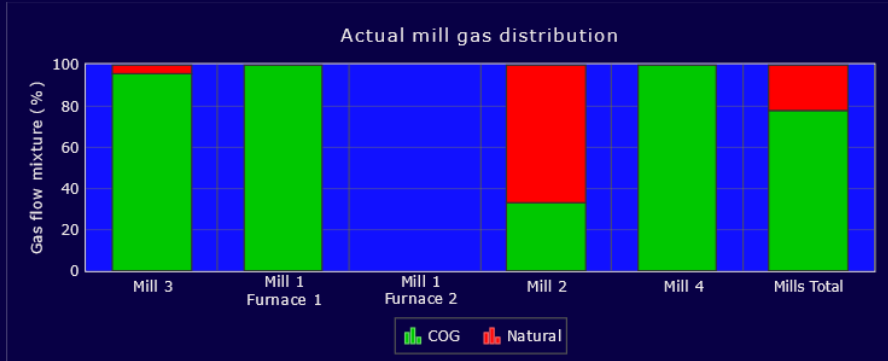
4.5 Implementation of the real-time optimisation system

To implement the optimisation model on the plant a real-time system was required. The real-time optimisation system described in Section 3.4 was implemented on the plant. The optimisation model used the furnace characteristics in the system. Data of each furnace was read directly from the control system to the optimisation system. The gas network was then optimised for reduced natural gas consumption.

A dashboard was developed for the optimisation system. A screenshot to indicate the design of the optimisation system dashboard is shown in Figure 4-16. The dashboard was displayed in the gas distribution network control room. It provided the control room operator with information to assist with decision making for the optimal distribution of coke oven and natural gas.

Keeping with the design developed in Section 3.4 the dashboard has a few elements with information. The actual distribution of gas is the first displayed element in the upper left of the dashboard. The results of the optimisation algorithm are displayed directly below this. The total amount of COG in the system can be adjusted and then optimised. A table with the specific changes required to the gas distribution is below this. On the right-hand side of the dashboard, a summary of the day's gas consumption for a selected furnace is displayed in a line graph and a table.

Plant gas distribution optimisation



Mill furnace	Energy	COG mixture		Cost	Lost opportunity
	Total GJ	Actual %	Optimised %	Total R	Natural gas R
Mill 3	662	99	96	35 890	-1 819
Mill 1 - Furnace 1	2 911	100	98	156 909	-9 111
Mill 1 - Furnace 2	0	0	0	0	0
Mill 2	2 198	80	100	126 989	49 013
Mill 4	2 158	91	87	120 514	-9 319
Mills Total	7 929	93	95	440 302	28 765

Adjust total COG (1000m³/h):

	Mill 3	Mill 1-1	Mill 1-1	Mill 2	Mill 4	Mills Total
	1000m ³ /h	1000m ³ /h	1000m ³ /h	1000m ³ /h	1000m ³ /h	1000m ³ /h
COG	2.6	8.98	0	2.03	0.84	14.45
Natural gas	0.11	0	0	4.07	0	4.19
COG - Optimise	2.79	5.62	0	6.14	0	14.55
Natural-Optimise	0	1.77	0	0	0.38	2.15
COG +/-	0.19	-3.37	0	4.11	-0.84	0.1
Natural +/-	-0.11	1.77	0	-4.07	0.38	-2.04

Figure 4-16: Real-time optimisation system dashboard

4.6 Verification of real-time optimisation system

4.6.1 IMPLEMENTATION PERIOD ON CASE STUDY

The optimisation system as described in the previous section was made available to the plant control room operators. This section shows the results of two periods where the system was used to optimise the COG distribution on the works. Each period had a four-day duration.

The result of the two implementation periods can be seen in Figure 4-17 and Figure 4-18. The figures display the total coke oven and natural gas being distributed to the mills. The system optimisation predicted the output for natural gas is also displayed. The optimised natural gas distribution and the actual gas consumption will be identical when the gas distribution in the system has been completely optimised.

The natural gas consumption for mill 2 is displayed since it is the least efficient on this gas. The optimisation system always moved natural gas away from the mill. Mill 2 did not operate on natural gas in the two implementation periods, except for a short time on 31 May 2017 when a large reduction in COG production occurred. This was, however, quickly rectified.

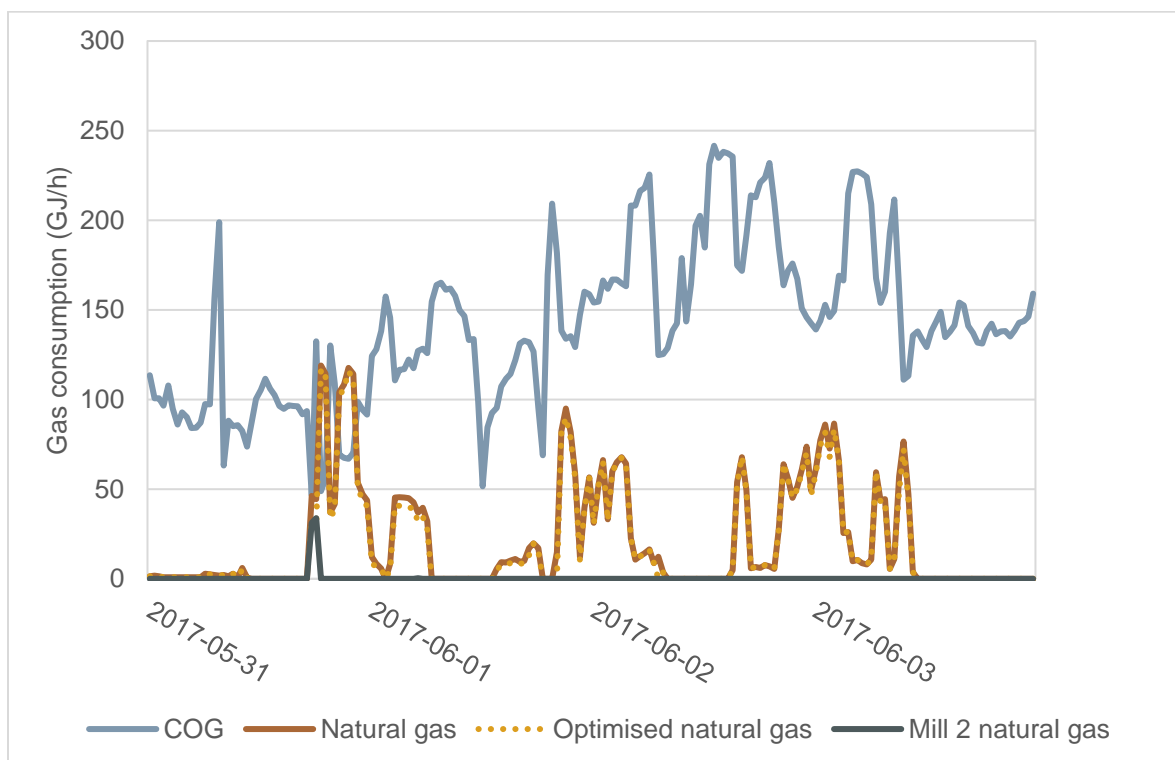


Figure 4-17: First implementation period optimisation results

The first implementation period shown in Figure 4-17, indicated good results. A minimal lost opportunity occurred over the testing period. Several instances of COG shortage occurred throughout the period. This can be seen where there was an increase in natural gas consumption that corresponded to a decrease in COG consumption. For the most part, the optimisation system's suggestion was followed.

The results for the end and start of June 2nd and 3rd respectively were exceptional. A drop in COG indicated a gas shortage that was filled with natural gas, the optimisation system was followed precisely. The gas consumption remained stable for the entire period, which was also good for energy efficiency.

The second implementation period is shown in Figure 4-18 also had an opportunity for natural gas distribution optimisation. The optimisation system output was followed as was allowed. There were, however, instances where plant operational constraints prohibited the use of COG at mill 1. This was caused by pressure loss in the COG line to the mill, natural gas was required on the 16th and 17th of June 2017. The performance on those days was reduced. Contrary to this, the optimisation model was followed exactly on the 18th of June, the result was favourable.

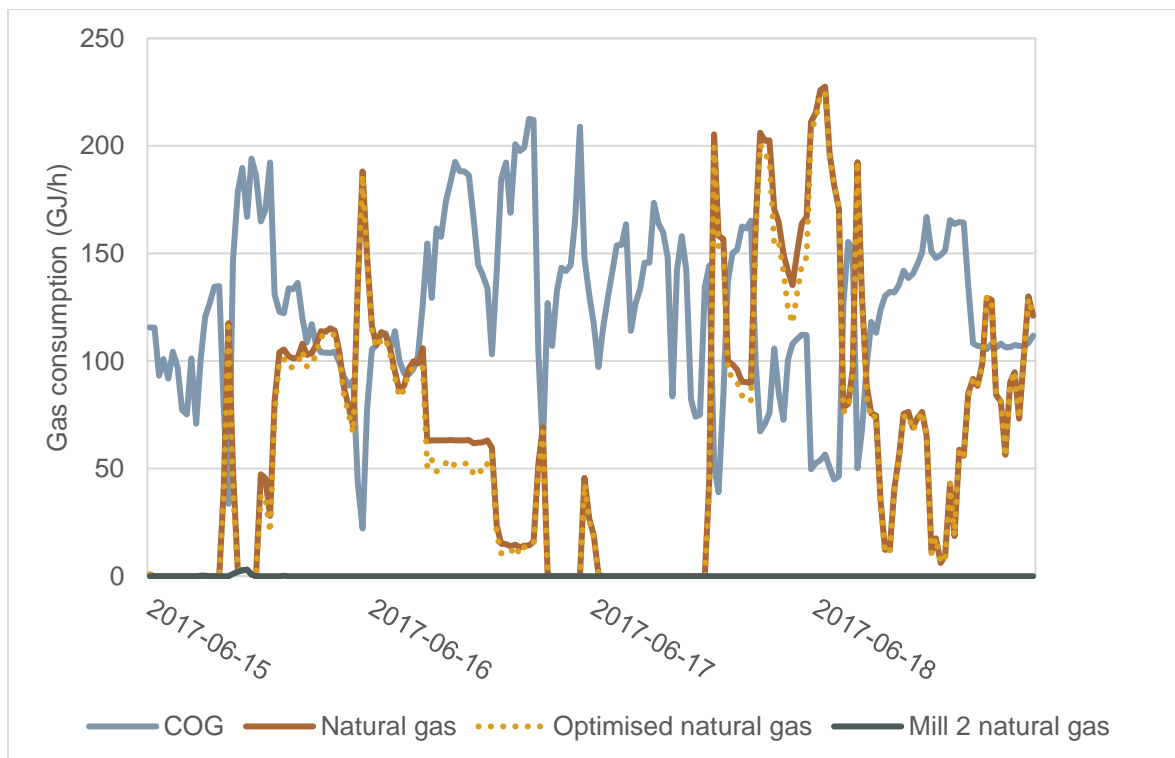


Figure 4-18: Second implementation period optimisation results

4.6.2 QUANTIFICATION OF OPTIMISATION SYSTEM BENEFIT

The process laid out in Section 3.5 was followed to determine the performance of the optimisation system in the implementation period. Data from 1 November 2017 to 31 May 2017 was used to develop a baseline against which the current plant performance can be measured. The data used was the COG and natural gas consumptions for each mill in hourly intervals.

The data was passed to the optimisation system to get an optimal gas distribution as in Section 4.4. The results of the optimisation of each data point can be seen in Figure 4-19. The actual natural gas consumption of the mills is plotted against the optimisation results. The data is sorted according to increasing optimised natural gas consumption. Also displayed is the hourly lost opportunity in GJ. This is the difference in the actual natural gas consumption compared to the optimisation result for each data point.

The purpose of the optimisation system is to reduce the natural gas consumption of the mills. This can be seen in the figure where the optimised natural gas consumption of the system is lower than the actual consumption. Figure 4-20 indicates the averaged results of the data. Also displayed is the averaged COG consumption of the mills. The performance of the optimisation system will be calculated by comparing the lost opportunity of the baseline period and the system implementation period.

There were certain periods that needed to be excluded from the calculation of the system performance. These instances were when:

- The total gas distribution to the mills was higher than 95% natural gas;
- The total gas distribution to the mills was lower than 5% natural gas;
- The measured gas consumption values to the furnaces were 20% higher than the determined furnace possible maximum load. This was in cases where the plant measurements were incorrect or out of range;
- No optimisation result was returned from the optimisation model; and
- No precedent was found in the baseline period, no performance will be calculated.

The baseline data was grouped according to furnace operational status. The furnaces' operational statuses are indicated in Table 4-6. The grouping of the baseline data results is shown in Table 4-7.

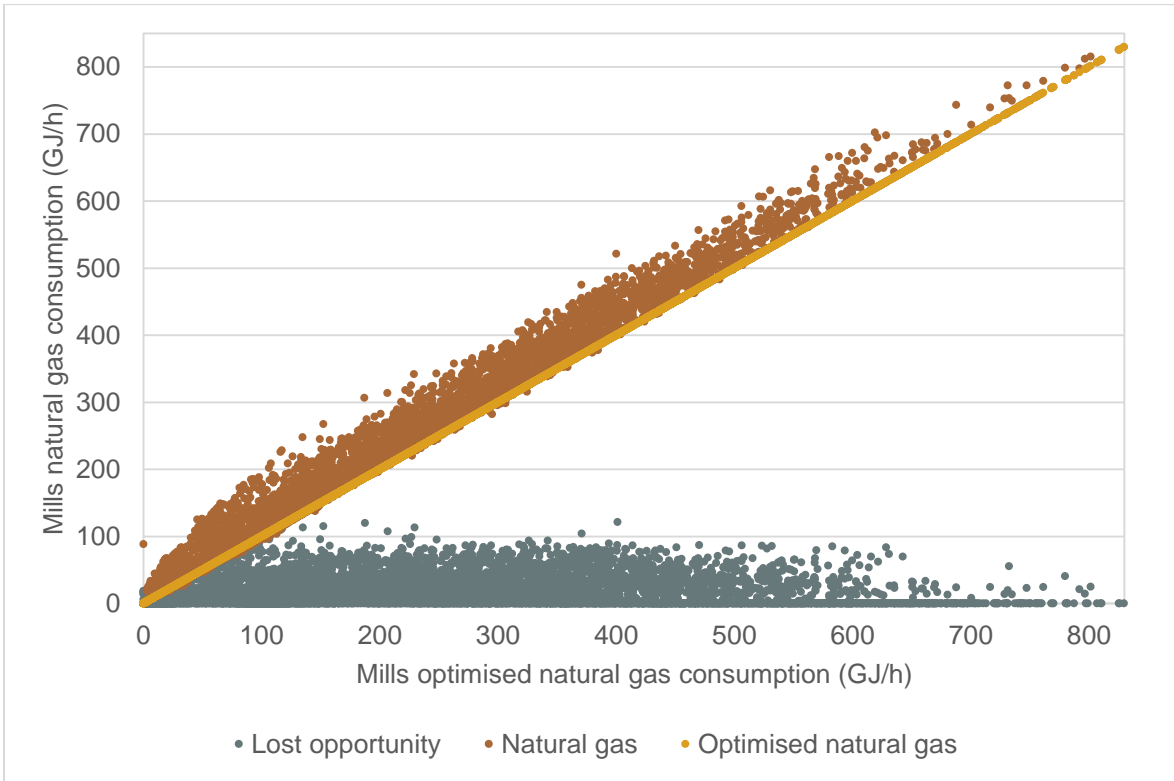


Figure 4-19: Baseline period optimisation results

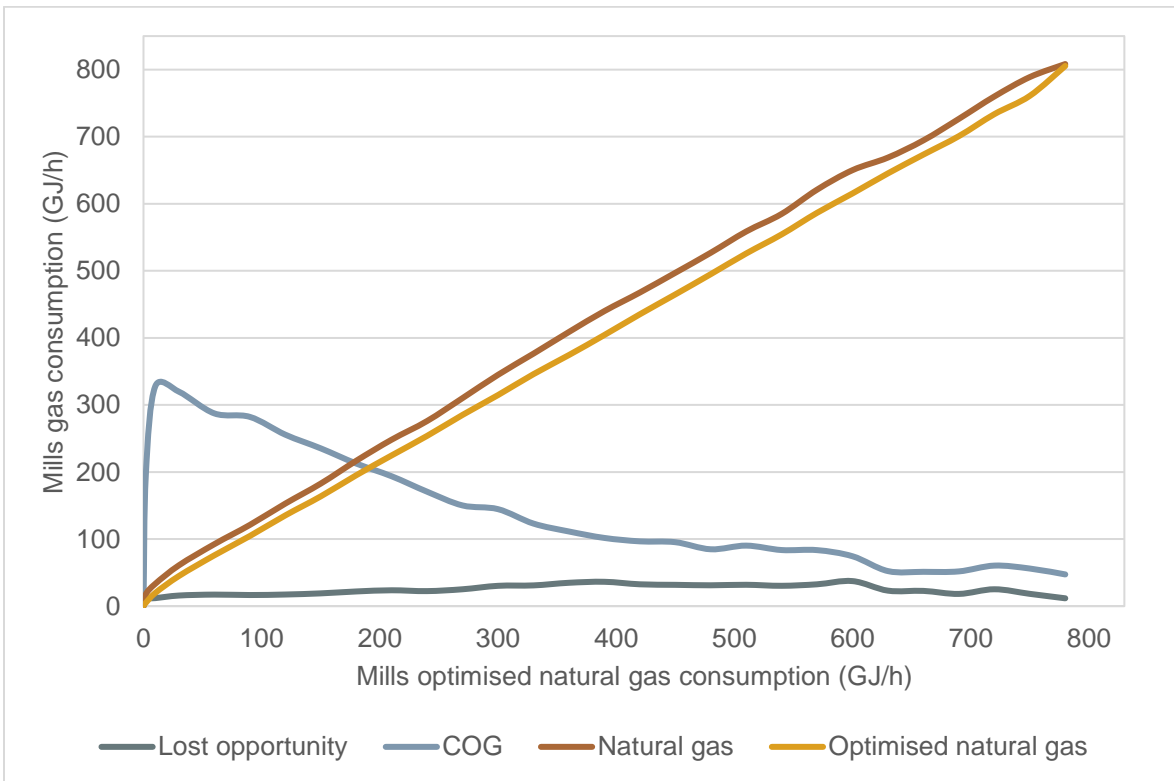


Figure 4-20: Baseline period averaged optimisation results

Table 4-6: Possible furnace operational status configurations

STATUS #	MILL 1 FURNACE 1	MILL 1 FURNACE 2	MILL 2	MILL 3	MILL 4
1	Off	Off	Off	Off	Off
2	Off	Off	Off	Off	On
3	Off	Off	Off	On	Off
4	Off	Off	Off	On	On
5	Off	Off	On	Off	Off
6	Off	Off	On	Off	On
7	Off	Off	On	On	Off
8	Off	Off	On	On	On
9	Off	On	Off	Off	Off
10	Off	On	Off	Off	On
11	Off	On	Off	On	Off
12	Off	On	Off	On	On
13	Off	On	On	Off	Off
14	Off	On	On	Off	On
15	Off	On	On	On	Off
16	Off	On	On	On	On
17	On	Off	Off	Off	Off
18	On	Off	Off	Off	On
19	On	Off	Off	On	Off
20	On	Off	Off	On	On
21	On	Off	On	Off	Off
22	On	Off	On	Off	On
23	On	Off	On	On	Off
24	On	Off	On	On	On
25	On	On	Off	Off	Off
26	On	On	Off	Off	On
27	On	On	Off	On	Off
28	On	On	Off	On	On
29	On	On	On	Off	Off
30	On	On	On	Off	On
31	On	On	On	On	Off
32	On	On	On	On	On

Table 4-6 indicates the different furnace operational statuses. These statuses were used to group the baseline data. A furnace was considered on if the furnace load, calculated with the furnace characterisation models, was higher than 30%. There were 32 different combinations that the five furnaces can be operated in.

Table 4-7: Baseline period lost energy savings opportunity for furnace configurations

STATUS #	NATURAL GAS TO MILLS [GJ/h]								
	Low	0	20	100	200	300	400	500	600
High	20	100	200	300	400	500	600	900	
1		10.3	21.6	26.1	35.2	38.0	36.7	29.1	
2		14.8	39.4	21.5	42.3	44.8	32.8	73.5	
3			26.8	27.1	25.8	20.2	18.9	19.8	
4			9.3	23.8	21.8				
5	25.6	24.4	19.6	26.0	41.9	33.7	20.9	8.5	
6	9.4	24.9	24.2	30.1	35.3	54.8	9.5		
7	4.1	4.1	10.5	11.6	14.7	17.4			
8	4.1	6.8	10.7	10.3	14.8				
9	23.2	11.6	21.4	38.9	50.9	44.9	25.5		
10	18.4	19.7	34.4	55.6	56.2	55.4	14.4		
11	7.9	14.8	15.1	12.2	8.6	8.1	9.1		
12	1.9	5.8	6.3	6.1	5.8	5.7			
13	15.8	22.3	26.6	30.7	18.6	15.8			
14	8.2	21.3	30.0	14.6	8.6				
15	2.2	12.7	8.3	11.0	14.4				
16		10.4	5.4						
17		16.6	30.5	23.9	35.0	37.4	39.1	26.3	
18		35.8		43.4	57.1	44.8	19.7		
19	19.4	28.0	18.8	29.5	25.4	21.6	14.6	20.4	
20		29.2		14.7	23.3				
21	21.7	13.7	17.3	24.9	40.1	28.1	22.6	36.4	
22	14.4	26.0	31.1	33.1	20.0				
23		4.3	16.6	12.7	13.1	13.4			
24	4.6	6.1	11.5	11.6					
25		6.8	18.2	33.0	41.1	33.7	14.9	17.9	
26	1.8	11.6	35.6	34.5	51.1	44.3			
27	1.5	12.9	11.0	12.8	10.9	17.1			
28	2.8	11.1	10.4	13.9	15.0				
29	17.4	12.1	29.3	21.9	12.7				
30	10.7	22.1	10.7	4.2					
31	15.0	6.7	6.3	15.2	19.3				
32	1.8	6.8	7.0	11.3					

Table 4-7 indicates the results of the baseline data grouping. The data was grouped by the possible furnace operational statuses. Further, the data was grouped by the amount of natural gas going to the mills in GJ per hour. A low and high threshold was used for the grouping.

To use the baseline table, one must determine the current operational status of the plants and the natural gas going to the mills. The baseline lost opportunity is then read from the table. The baseline value for each period under assessment is required to determine the improvement of the optimisation system. The results can then be aggregated.

The aggregated results can then be multiplied by the natural gas tariff to determine the energy cost saving effect. Table 4-8 indicates the effective price in Rand per GJ [R/GJ] of natural gas for December 2016, as published by the South African Department of Energy [76]. The prices for each consumer is determined based on their gas consumption in gigajoule per annum [GJ/a]. The price groups are divided into 6 classes, as well as the maximum possible price.

Table 4-8: Natural gas price for South Africa grouped by annual gas consumption [76]

MONTH	MAX	CLASS 1	CLASS 2	CLASS 3	CLASS 4	CLASS 5	CLASS 6
GJ/a	Low	0	5 000	15 000	40 000	100 000	400 000
	High	5 000	15 000	40 000	100 000	400 000	>
Dec 2016	R 135	R 83.42	R 83.41	R 75.30	R 50.20	R 45.17	R 40.15

4.6.3 RESULTS OF IMPLEMENTATION PERIOD

The results of the implementation period are displayed in Table 4-9. The table indicates the daily totals of the actual COG and natural gas consumption. The results were then filtered with the required exclusions to determine the availability of the system to optimise the natural gas consumption. The utilisation of the system was also calculated to indicate to what extent it had been followed when optimisation was possible. Finally, the improvement in energy consumption is indicated in GJ with the corresponding percentage.

A total improvement in natural gas consumption of 378 GJ or 3% was observed over the eight-day implementation period. This result included the period of the 16th and 17th of June 2017 where mill 1 could not be placed on COG. The baseline indicated an unfavourable result, especially on the 17th where the result indicated a negative impact of 80 GJ. Excluding this period from the assessment results in an overall improvement of 4%.

Of note, were the results for the 2nd and 18th of June 2017. Where the improvement observed was 13% and 7% respectively. The optimisation system could be followed on these periods as can be seen from the high utilisation figure of 95% and 97%. This was in line with the predicted improvement of the scoping period.

Table 4-9: Implementation period results

DATE	ACTUAL GAS		SYSTEM		IMPROVEMENT	
	COG	Natural	Availability	Utilisation	Natural gas	
	GJ	GJ	%	%	GJ	%
2017-05-31	4 527	1 028	29%	86%	3	0%
2017-06-01	6 316	927	60%	69%	19	2%
2017-06-02	8 859	1 184	44%	95%	121	13%
2017-06-03	7 455	898	21%	60%	33	5%
2017-06-15	5 527	2 627	56%	59%	70	3%
2017-06-16	6 998	2 502	81%	59%	26	1%
2017-06-17	5 693	3 379	50%	8%	-80	-2%
2017-06-18	5 621	4 305	65%	97%	186	7%
Total	50 996	16 850	51%	67%	378	3%

4.7 Discussion of results

Throughout the implementation period, the optimisation system had some shortcomings. The first of which were instances in real-time that could not be optimised. This was seen mainly with low or high natural gas going to the furnaces. The optimisation system compensated for this since there was minimal gas distribution improvement opportunity in these instances. However, an improved optimisation algorithm that can increment in smaller steps and seek the correct solution quicker will be beneficial as well as more robust.

Another shortfall of the system was that situational operational constraints were not taken into consideration. This was seen in the implementation period where mill 1 could not operate on COG due to line pressure complications. It would be beneficial if the system can exclude a mill, that is temporarily constrained, from the optimisation algorithm. To achieve this, an additional input would be required from the operator to indicate the constraint.

The shortcomings were situational and the system benefits far outweigh them. The system assisted the gas network operator in deciding what the best operational configuration would be for the lowest possible natural gas consumption. This was done by the system in real-time. Additionally, when the operator was warned of an imminent change in the COG supply, the effect on the system could be predicted. Changes to the gas distribution could then be made accordingly.

The consumption of natural gas by the furnaces in the network can be minimised. The result of all this was that the plant could save costs on its natural gas bill. The result was a direct cost saving. The analysis of the results of the backward test in Section 4.4 and the implementation period in Section 4.6 follows.

The optimisation model was applied to historical data in a backward test to determine the possible impact of the system. The optimisation model indicated a missed opportunity of 145 TJ for the 10-month scoping period. This was a 9% loss in opportunity for saving on natural gas consumption. The resultant energy cost saving, based on the class 6 tariff in Table 4-8, for the period would have been approximately R 5.8 million. This saving excludes other billed quantities such as taxes and transmission costs.

Although it was difficult to determine the exact improvement in natural gas consumption, a reduction of 13%, 7% and 5% in daily natural gas consumption was observed in the implementation period. The overall improvement in natural gas consumption was 3% when including all data and 4% when excluding operational restrictions. Based on the natural gas consumption for 2016, the cost saving projection at 4% was R 2.3 million per year excluding other charges.

The methodology developed in this study provides advantages over existing solutions in literature. The advantages of the methodology are divided into three novel contributions that are set out in Section 1.7.

The first novel contribution is an energy characterisation model for a reheating furnace. The model used limited information and measurements to simulate the energy consumption for a furnace for different gas operation mixtures under varying furnace production loads. Existing benchmarking methods, software tools, CFD and simulation models in literature could not achieve this, as summarised in Section 2.2.

The second novel contribution of this study is a new optimisation model for different gases in a gas distribution network. The model used an integrated network of furnace energy characterisation models. The model works with only the total gas flow for each fuel gas per furnace. Existing optimisation models for the whole steel facility look to improve the thermal utilisation and production flow. Existing optimisation models focus on temperature control and electricity generation improvement. The limitations of these models are summarised in Section 2.3.

The final novel contribution is the real-time optimisation system verified in this chapter. The system used the optimisation model implemented in Section 4.6 to simulate and optimise the gas distribution to the reheating furnaces in real-time. Existing production scheduling systems and model predictive controllers in literature cannot achieve this. The limitations of these systems are summarised in Section 2.4.

4.8 Summary

To validate the methodology that was developed in Chapter 3 it was implemented on a case study in this chapter. The plant in this case study was a steelmaking facility based in South Africa. The plant had four steel mills equipped with five reheating furnaces. The plant produced COG as a by-product gas of the coke making process that was consumed by the reheating furnaces amongst other consumers. Shortage of gas was filled with the purchase of natural gas from an outside supplier.

The distribution of the COG throughout the plant and to the furnaces was determined by a human operator. The problem was that a human operator cannot determine the efficiency of a reheating furnace on different gases in real-time while operating the gas distribution network. This meant that the network was operated inefficiently when gas shortages occurred and additional energy costs were incurred.

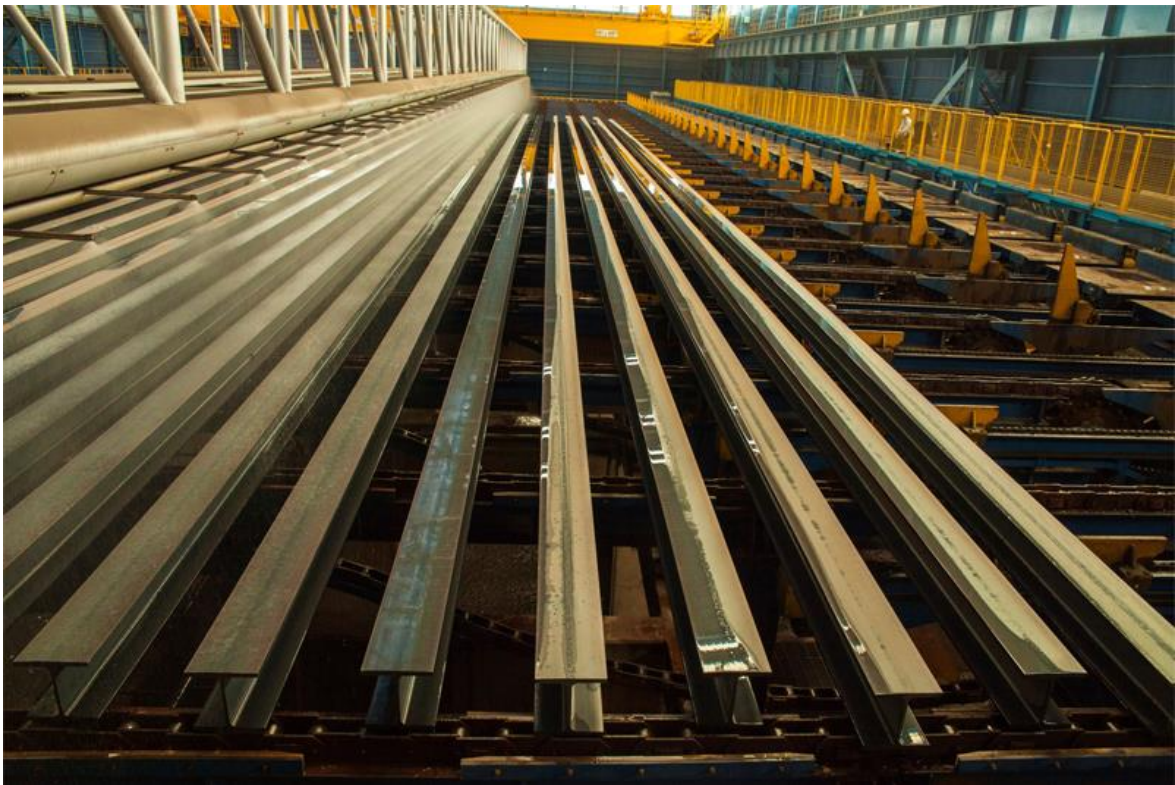
The reheating furnaces in the case study were modelled following the methodology presented. The models were presented as a single regression line of the maximum furnace energy consumption. The characterisation models of the five furnaces can simulate the furnace energy consumption for different loads and fuel gas supply mixtures. They can be used to simulate the effect of changes to the furnace gas supply. The model for the furnace in mill 3 was verified with the experimental procedure laid out in the methodology.

The five characterisation models were configured in an integrated network for energy consumption simulation. The influence of changes to the network could then be simulated for each furnace's energy consumption. The simulation model was then set up in an optimisation model for reduced energy costs. The optimisation model was back-tested on historical data to determine the benefit of implementing the model. It was found that a maximum natural gas cost reduction of 9% was possible for the 10-month test period.

A real-time optimisation system was developed and implemented for a period to verify the system. The system's optimisation was based on the developed model. The system optimised the distribution of COG to the furnaces. Changes to the COG supply can also be simulated and optimised. The model was implemented on the facility in two four-day periods.

The system benefit quantification model was developed based on the methodology. A net increase in natural gas consumption was observed when gas network limitations meant that the system suggestion could not be followed. It was found that when the system suggestion was followed a natural gas consumption decrease of 13%, 7% and 5% per day was possible. The overall decrease in natural gas consumption was 3% including all scenarios and 4% when excluding operational restrictions. Based on the natural gas consumption for the plant in 2016, the cost saving projection at 4% was R 2.3 million per year excluding other charges.

5 CONCLUSION



Finished products on the cooling bank. ⁸

⁸ Sulb Company, *Finished product on the cooling bank 2*, 2014 [Online]. Available: <http://www.sulb.com.bh/Media/HSM/>. [Accessed 8 October 2017]

5.1 Review of work completed

This chapter concludes the study by reviewing the shortcomings and the benefits of the research conducted. The objective of this study was to develop a research methodology that can be used in an integrated steelmaking facility to reduce operational costs. The method delivered a gas network distribution optimisation system that was validated on a case study. The plant in this case study is a steelmaking facility based in South Africa. The plant has four steel mills equipped with five reheating furnaces.

The use of the system resulted in a reduction of purchased natural gas in the reheating furnaces and the cost thereof. The optimisation model was applied to historical data in a backward test to determine the possible impact of the system. The optimisation model indicated a missed opportunity of 145 TJ for the 10-month scoping period. This is a 9% loss in opportunity for saving on natural gas consumption. The resultant energy cost saving for the period would have been approximately R 5.8 million. This saving excludes other billed quantities such as taxes and transmission costs.

A reduction of 13%, 7% and 5% in daily natural gas consumption was observed during the actual system implementation period. The overall improvement in natural gas consumption was 3% when including all data and 4% when excluding operational restrictions. Based on the total natural gas consumption for 2016, the cost saving projection at a 4% natural gas reduction is R 2.3 million per year excluding other charges.

The system did have a few shortcomings in the optimisation methodology. The optimisation model only calculated the least expensive solution for the gas distribution. Whenever the plant circumstances dictated a specific operational configuration, the system would continue to suggest this result. Cases like these were seen in the implementation period. It would be beneficial for the system to allow for the locking of a furnace's operational configuration. This would mean that the rest of the network can still be further optimised.

Another shortcoming of the optimisation methodology was the optimisation algorithm used. The developed algorithm is a simplified approach to optimising the system. However, the algorithm had trouble computing some boundary operational configurations. Its simplicity will also hamper its usefulness if finer optimisation results are required since the number of calculations increases exponentially. However, the performance in the case of this study was adequate.

There are numerous benefits in the use of the system. The reheating furnace characterisation model that was developed is a simplified and elegant solution to multiple challenges with these types of models. The model can simulate the furnace energy consumption under varying loads and with different fuel gas supplies in real-time. This means that when they are used in the optimisation system, the effect of changes in the system can quickly be predicted and acted upon.

The system was designed to assist the operator with the optimisation of the fuel gas distribution network. The operator can focus on other essential tasks without keeping the efficiency of the reheating furnace's effect on the gas distribution in mind. The system optimises the network in real-time, but can also be used to simulate what the effect of changes in the network will be. This functionality can be used for planning by the operator. The net effect of this is the improvement of the fuel gas distribution and the reduction of purchased gas consumption.

The optimisation system requires limited information from the plant to be developed and set up. The system only requires the total gas flow of the different gases consumed by each reheating furnace in the network. It can be set up at a central control location where this information is available. Most other available models require much more detailed measurements for these types of calculations and simulations.

The optimisation system does not require high computational power to simulate and optimise the gas distribution network. This is due to the models being simplified in nature. What it also means is that the system can be set up on existing infrastructure without affecting the system's performance.

The system can be implemented at a low cost. The required measurements are available in even the older plants. This means that no new measurement equipment must be installed. Because the system can be implemented on an existing control system, no new equipment needs to be purchased. The specifications of a new system are also low if new equipment is desired. New equipment would include a network server or computer. The system can be implemented by qualified personnel on site. It is estimated that the system can be implemented in a calendar month by a single engineer or technician.

5.2 Recommendations

This section details the recommendations for future studies that can extend the research conducted in this study. As mentioned in the previous section, the optimisation algorithm used can be improved. Research can be done on other available optimisation algorithms that require fewer calculations to complete and can optimise in smaller increments.

The optimisation methodology that was developed in this study can be used in other systems and even in other industries. The system optimises the distribution of by-product gas to reduce the consumption of other fuel gases. Other systems with the same objective will also benefit with the use of the developed methodology and system. In the steel industry, examples of the systems that meet this requirement are the coke ovens and boilers.

The reheating furnace is a popular topic of research. There are a few recommendations for further research that can be made. This was observed in the completion of this study. The furnace operates differently on different fuel gases and this has a direct influence on efficiency. The different burners in the zones of the furnace also operate differently on different gases. It is recommended that the effect of the changing of fuel gas to each zone be characterised in a similar manner as was done in this study. There may be room for the optimisation of specific furnace configurations.

This study places focus and importance on the improvement of the gas network in a way that requires low capital expenditure and can be implemented on the system without changing the components. However, the characterisation of the furnaces revealed that some furnaces are much worse on certain fuel gas types than other similar furnaces in the network. It is recommended that the cause of this inefficiency be investigated. This may require capital expenditure to implement. However, the improvement of the furnace energy characteristic may allow for more scenarios where the network efficiency is optimum.

6 REFERENCES

- [1] World Steel Association, "World steel in figures 2017," Brussels, 2017.
- [2] T. P. Stewart, E. J. Drake, S. M. Bell, J. Wang, and R. E. Scott, "Surging steel imports put up to half a million U.S. jobs at risk," Washington, D.C., 2014.
- [3] G. H. Popescu, E. Nica, R. O. Ștefănescu-Mihăilă, and G. Lăzăroiu, "The United States (U.S.) steel import crisis and the global production overcapacity till 2016," *Metalurgija*, vol. 55, no. 3, pp. 538–540, 2016.
- [4] World Steel Association, "Steel Statistical Yearbook 2017," 2017.
- [5] R. A. Dondofema, S. Matope, and G. Akdogan, "South African iron and steel industrial evolution: an industrial engineering perspective," *South African Journal of Industrial Engineering*, vol. 28, no. May, pp. 103–113, 2017.
- [6] X. Zhang, J. Zhao, W. Wang, L. Cong, and W. Feng, "An optimal method for prediction and adjustment on byproduct gas holder in steel industry," *Expert Systems with Applications*, vol. 38, no. 4, pp. 4588–4599, 2011.
- [7] South African Department of Energy, "Commodity flows and energy balances," 2016. [Online]. Available: http://www.energy.gov.za/files/energyStats_frame.html.
- [8] World Steel Association, "Energy use in the steel industry," 2014.
- [9] South African National Treasury, "Carbon Tax Policy Paper," 2013.
- [10] D. E. Wiley, M. T. Ho, and A. Bustamante, "Assessment of opportunities for CO₂ capture at iron and steel mills: An Australian perspective," *Energy Procedia*, vol. 4, pp. 2654–2661, 2011.
- [11] M. T. Ho, A. Bustamante, and D. E. Wiley, "Comparison of CO₂ capture economics for iron and steel mills," *International Journal of Greenhouse Gas Control*, vol. 19, pp. 145–159, 2013.
- [12] B. Lu, D. Chen, G. Chen, and W. Yu, "An energy apportionment model for a reheating furnace in a hot rolling mill - A case study," *Applied Thermal Engineering*, vol. 112, pp. 174–183, 2017.
- [13] E. Worrell, P. Blinde, M. Neelis, E. Blomen, and E. Masanet, "Energy efficiency improvement and cost saving opportunities for the U.S. iron and steel industry," Berkeley, 2010.
- [14] US Environmental Protection Agency (EPA), "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry," 2012.
- [15] J. C. M. Farla and K. Blok, "The quality of energy intensity indicators for international

- comparison in the iron and steel industry,” *Energy Policy*, vol. 29, pp. 523–543, 2001.
- [16] Lockheed Martin, “Ironmaking Process Alternatives Screening Study,” 2000.
- [17] E. Worrell, L. Price, and N. Martin, “Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Iron and Steel Sector,” *Energy*, vol. 26, pp. 513–536, 1999.
- [18] H. S. O. Santos, P. E. M. Almeida, and R. T. N. Cardoso, “Fuel costs minimisation on a steel billet reheating furnace using genetic algorithms,” *Modelling and Simulation in Engineering*, vol. 2017, 2017.
- [19] Britannica Academic, “Heat of reaction,” *Encyclopaedia Britannica*, 2015. [Online]. Available: <http://academic.eb.com.nwulib.nwu.ac.za/EBchecked/topic/492712/heat-of-reaction?anchor=ref99163>. [Accessed: 27-Sep-2015].
- [20] H. N. Kong, “A green mixed integer linear programming model for optimization of byproduct gases in iron and steel Industry,” *Journal of Iron and Steel Research International*, vol. 22, no. 8, pp. 681–685, 2015.
- [21] G. I. Atwater, J. E. Carruthers, J. P. Riva, L. H. Solomon, and A. L. Waddams, “Natural gas,” *Encyclopaedia Britannica*, 2015. [Online]. Available: <http://academic.eb.com.nwulib.nwu.ac.za/EBchecked/topic/406163/natural-gas>. [Accessed: 27-Sep-2015].
- [22] Britannica Academic, “Liquefied petroleum gas,” *Encyclopaedia Britannica*, 2015. [Online]. Available: <http://academic.eb.com.nwulib.nwu.ac.za/EBchecked/topic/343014/liquefied-petroleum-gas>. [Accessed: 27-Sep-2015].
- [23] A. Azadeh, Z. Raoofi, and M. Zarrin, “A multi-objective fuzzy linear programming model for optimization of natural gas supply chain through a greenhouse gas reduction approach,” *Journal of Natural Gas Science and Engineering*, vol. 26, pp. 702–710, 2015.
- [24] J. Yang, J. Cai, W. Sun, and J. Huang, “Optimal allocation of surplus gas and suitable capacity for buffer users in steel plant,” *Applied Thermal Engineering*, vol. 115, pp. 586–596, 2017.
- [25] E. Worrell, L. Price, M. Neelis, C. Galitsky, and Z. Nan, “World Best Practice Energy Intensity Values for Selected Industrial Sectors,” 2007.
- [26] J. Andersen and B. Hyman, “Energy and material flow models for the U.S. steel industry,” *Energy*, vol. 26, no. 2, pp. 137–159, 2001.
- [27] A. Hasanbeigi, L. Price, Z. Chunxia, N. Aden, L. Xiuping, and S. Fangqin, “Comparison of iron and steel production energy use and energy intensity in China

- and the U.S.," *Journal of Cleaner Production*, vol. 65, pp. 108–119, 2014.
- [28] P. Jin, Z. Jiang, C. Bao, S. Hao, and X. Zhang, "The energy consumption and carbon emission of the integrated steel mill with oxygen blast furnace," *Resources, Conservation and Recycling*, vol. 117, pp. 58–65, 2015.
- [29] J. K. Myalapalli, "Performance assessment of steel reheating furnace," in *International Conference on Energy Systems and Applications (ICESA)*, 2015, pp. 141–145.
- [30] M. Si, S. Thompson, and K. Calder, "Energy efficiency assessment by process heating assessment and survey tool (PHAST) and feasibility analysis of waste heat recovery in the reheat furnace at a steel company," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 6, pp. 2904–2908, 2011.
- [31] S. Thompson and M. Si, "Strategic analysis of energy efficiency projects: Case study of a steel mill in Manitoba," *Renewable and Sustainable Energy Reviews*, vol. 40, pp. 814–819, 2014.
- [32] W. Chen, X. Yin, and D. Ma, "A bottom-up analysis of China's iron and steel industrial energy consumption and CO₂ emissions," *Applied Energy*, vol. 136, no. 0, p. , 2014.
- [33] C.-T. Hsieh, M.-J. Huang, S.-T. Lee, and C.-H. Wang, "Numerical modeling of a walking-beam-type slab reheating furnace," *Numerical Heat Transfer, Part A*, vol. 53, no. 9, pp. 966–981, 2008.
- [34] J. M. Casal, J. Porteiro, J. L. Míguez, and A. Vázquez, "New methodology for CFD three-dimensional simulation of a walking beam type reheating furnace in steady state," *Applied Thermal Engineering*, vol. 86, pp. 69–80, 2015.
- [35] G. Tang, B. Wu, D. Bai, Y. Wang, R. Bodnar, and C. Q. Zhou, "Modeling of the slab heating process in a walking beam reheating furnace for process optimization," *International Journal of Heat and Mass Transfer*, vol. 113, pp. 1142–1151, 2017.
- [36] C. K. Tan, J. Jenkins, J. Ward, J. Broughton, and A. Heeley, "Zone modelling of the thermal performances of a large-scale bloom reheating furnace," *Applied Thermal Engineering*, vol. 50, no. 1, pp. 1111–1118, 2013.
- [37] B. Mayr, R. Prieler, M. Demuth, L. Moderer, and C. Hochenauer, "CFD analysis of a pusher type reheating furnace and the billet heating characteristic," *Applied Thermal Engineering*, vol. 115, pp. 986–994, 2017.
- [38] K. Guo, W. Shi, and D. Wu, "Experiment research and simulation analysis of regenerative oxygen-enriched combustion technology," in *Energy Procedia*, 2015, vol. 66, pp. 221–224.
- [39] Y. Lu, H. Chen, and A. Xu, "Comparative study on special and non-special reheating

- furnace mode based on simulation technology,” *Metalurgia international*, vol. 2013, no. 65, pp. 1–6, 2013.
- [40] D. Wild, T. Meurer, and a. Kugi, “Modelling and experimental model validation for a pusher-type reheating furnace,” *Mathematical and Computer Modelling of Dynamical Systems*, vol. 15, no. 3, pp. 209–232, 2009.
- [41] T. Pongam, V. Khomphis, and J. Srisertpol, “System modeling and temperature control of reheating furnace walking hearth type in the setting up process,” *Journal of Mechanical Science and Technology*, vol. 28, no. 8, pp. 3377–3385, 2014.
- [42] A. Jaklič, F. Vode, and T. Kolenko, “Online simulation model of the slab-reheating process in a pusher-type furnace,” *Applied Thermal Engineering*, vol. 27, no. 5–6, pp. 1105–1114, 2007.
- [43] B. Lu, G. Chen, D. Chen, and W. Yu, “An energy intensity optimization model for production system in iron and steel industry,” *Applied Thermal Engineering*, vol. 100, pp. 285–295, 2016.
- [44] K. Matsuda, S. Tanaka, M. Endou, and T. Iiyoshi, “Energy saving study on a large steel plant by total site based pinch technology,” *Applied Thermal Engineering*, vol. 43, pp. 14–19, 2012.
- [45] L. Chen, B. Yang, X. Shen, Z. Xie, and F. Sun, “Thermodynamic optimization opportunities for the recovery and utilization of residual energy and heat in China’s iron and steel industry: A case study,” *Applied Thermal Engineering*, vol. 86, pp. 151–160, 2015.
- [46] X. Zhao, H. Bai, Q. Shi, X. Lu, and Z. Zhang, “Optimal scheduling of a byproduct gas system in a steel plant considering time-of-use electricity pricing,” *Applied Energy*, vol. 195, pp. 100–113, 2017.
- [47] X. Zhao, H. Bai, and J. Hao, “A review on the optimal scheduling of byproduct gases in steel making industry,” *Energy Procedia*, vol. 142, pp. 2852–2857, 2017.
- [48] V. B. de Oliveira Junior, J. G. C. Pena, and J. L. F. Salles, “An improved plant-wide multiperiod optimization model of a byproduct gas supply system in the iron and steel-making process,” *Applied Energy*, vol. 164, pp. 462–474, 2016.
- [49] L. Sun, D. Qu, and G. Liu, “A mixed integer programming model for gas distribution problem with complex gas applied characteristics,” *Journal of Computational Methods in Sciences and Engineering*, vol. 16, no. 4, pp. 865–875, 2016.
- [50] Y. Zeng, X. Xiao, J. Li, L. Sun, C. A. Floudas, and H. Li, “A novel multi-period mixed-integer linear optimization model for optimal distribution of byproduct gases, steam and power in an iron and steel plant,” *Energy*, vol. 143, pp. 881–899, 2018.

- [51] X. Zhao, H. Bai, X. Lu, Q. Shi, and J. Han, "A MILP model concerning the optimisation of penalty factors for the short-term distribution of byproduct gases produced in the iron and steel making process," *Applied Energy*, vol. 148, pp. 142–158, 2015.
- [52] W. H. Chen, Y. C. Chung, and J. L. Liu, "Analysis on energy consumption and performance of reheating furnaces in a hot strip mill," *International Communications in Heat and Mass Transfer*, vol. 32, no. 5, pp. 695–706, 2005.
- [53] A. Steinboeck, D. Wild, and A. Kugi, "Energy-efficient control of continuous reheating furnaces," in *IFAC Symposium on Automation in Mining, Mineral and Metal Processing*, 2013, vol. 16, pp. 359–364.
- [54] J. Y. Jang and J. B. Huang, "Optimization of a slab heating pattern for minimum energy consumption in a walking-beam type reheating furnace," *Applied Thermal Engineering*, vol. 85, pp. 313–321, 2015.
- [55] K. Chakravarty, S. Das, and K. Singh, "Identification and improvement in operating practices of reheating furnace to reduce fuel consumption in hot strip mill," *Ironmaking & Steelmaking*, vol. 40, no. 1, pp. 74–80, 2013.
- [56] A. Steinboeck, K. Graichen, and A. Kugi, "Dynamic optimization of a slab reheating furnace with consistent approximation of control variables," *IEEE Transactions on Control Systems Technology*, vol. 19, no. 6, pp. 1444–1456, 2011.
- [57] S. H. Han, D. Chang, and C. Huh, "Efficiency analysis of radiative slab heating in a walking-beam-type reheating furnace," *Energy*, vol. 36, no. 2, pp. 1265–1272, 2011.
- [58] J. G. Wang *et al.*, "Soft-sensing method for optimizing combustion efficiency of reheating furnaces," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 73, pp. 112–122, 2016.
- [59] X. Meixiang and C. Wei, "Walking Beam Furnace Temperature Control using Fuzzy Feed Forward Method in Steel Rolling Mill," in *32nd Chinese Control Conference*, 2013, pp. 3525–3528.
- [60] F. A. D. Oliveira, J. A. Carvalho, P. M. Sobrinho, and A. de Castro, "Analysis of oxy-fuel combustion as an alternative to combustion with air in metal reheating furnaces," *Energy*, vol. 78, pp. 290–297, 2014.
- [61] S. H. Han, S. W. Baek, S. H. Kang, and C. Y. Kim, "Numerical analysis of heating characteristics of a slab in a bench scale reheating furnace," *International Journal of Heat and Mass Transfer*, vol. 50, no. 9–10, pp. 2019–2023, 2007.
- [62] Z. Wang, Q. Wu, and T. Chai, "Optimal-setting control for complicated industrial processes and its application study," *Control Engineering Practice*, vol. 12, no. 1, pp. 65–74, 2004.

- [63] Z. Yang and X. Luo, "Optimal set values of zone modeling in the simulation of a walking beam type reheating furnace on the steady-state operating regime," *Applied Thermal Engineering*, vol. 101, pp. 191–201, 2016.
- [64] L. Merkert, I. Harjunkoski, A. Isaksson, S. Säynevirta, A. Saarela, and G. Sand, "Scheduling and energy - Industrial challenges and opportunities," *Computers and Chemical Engineering*, vol. 72, pp. 183–198, 2015.
- [65] J. A. Swanepoel, "Modelling for integrated energy optimisation in cement production plants," M.Eng. dissertation, North-West University, South Africa, 2012.
- [66] S. W. Van Heerden, "A dynamic optimal control system for complex compressed air networks," PhD thesis, North-West University, South Africa, 2016.
- [67] N. Tu, X. Luo, and T. Chai, "Two-stage method for solving large-scale hot rolling planning problem in steel production," in *Proceedings of the 18th World Congress The International Federation of Automatic Control (IFAC)*, 2011, vol. 18, pp. 12120–12125.
- [68] M. Suzuki, K. Katsuki, J. I. Imura, J. I. Nakagawa, T. Kurokawa, and K. Aihara, "Simultaneous optimization of slab permutation scheduling and heat controlling for a reheating furnace," *Journal of Process Control*, vol. 24, no. 1, pp. 225–238, 2014.
- [69] A. Goswami, R. K. Singh, A. Prasad, and S. Chowdhuri, "Mathematical model-based control system for silicon steel mill of Rourkela steel plant," *Procedia Technology*, vol. 4, pp. 867–872, 2012.
- [70] M. Gangadaran and S. Mitra, "Application of close loop expert system for heating control of rolling mill furnaces in a steel plant," in *IEEE First International Conference on Control, Measurement and Instrumentation (CMI)*, 2016, pp. 290–294.
- [71] A. Steinboeck, D. Wild, and A. Kugi, "Nonlinear model predictive control of a continuous slab reheating furnace," *Control Engineering Practice*, vol. 21, no. 4, pp. 495–508, 2013.
- [72] P. Laurinen and J. Röning, "An adaptive neural network model for predicting the post roughing mill temperature of steel slabs in the reheating furnace," *Journal of Materials Processing Technology*, vol. 168, no. 3, pp. 423–430, 2005.
- [73] A. Steinboeck, K. Graichen, D. Wild, T. Kiefer, and A. Kugi, "Model-based trajectory planning, optimization, and open-loop control of a continuous slab reheating furnace," *Journal of Process Control*, vol. 21, no. 2, pp. 279–292, 2011.
- [74] C. Wanli, K. Ning, and W. Daohong, "Dynamic furnace temperature setting research on combustion system of rolling mill reheating furnace," *Physics Procedia*, vol. 66, pp. 217–220, 2015.

- [75] Siemens VAI, "Siroll furnace optimization," Linz, 2013.
- [76] South African Department of Energy, "2017 South African energy prices statistics," Pretoria, 2017.

APPENDIX A DETAIL RESULTS

This appendix contains the detail data of the figures found in Section 4.2.

Table A-1: Mill production figures for 2016

PERIOD	MILL 1	MILL 2	MILL 3	MILL 4
	t	t	t	t
Jan 2016	95 020	26 610	31 391	57 195
Feb 2016	93 065	26 624	26 440	52 077
Mar 2016	94 527	30 755	22 432	40 197
Apr 2016	109 757	28 702	28 444	59 419
May 2016	98 055	27 611	27 216	58 810
Jun 2016	96 193	27 959	24 383	40 541
Jul 2016	103 928	27 378	29 648	56 610
Aug 2016	87 302	27 588	26 788	46 549
Sep 2016	106 740	5 524	31 127	44 185
Oct 2016	89 834	22 191	1 770	47 929
Nov 2016	86 777	27 493	27 627	52 875
Dec 2016	79 542	2 652	20 545	37 864
2016	1 140 739	281 087	297 810	594 253

Table A-2: Mill gas consumption figures for 2016

PERIOD	NATURAL GAS TO MILLS	COKE OVEN GAS TO MILLS	PRODUCTION
	TJ	TJ	Mt
Jan 2016	61 245	259 751	210 217
Feb 2016	58 381	231 449	198 206
Mar 2016	64 630	226 763	187 911
Apr 2016	161 692	215 433	226 322
May 2016	278 374	82 084	211 691
Jun 2016	195 325	121 198	189 076
Jul 2016	152 620	195 303	217 564
Aug 2016	155 361	164 892	188 227
Sep 2016	117 124	217 115	187 575
Oct 2016	80 451	236 694	161 725
Nov 2016	110 624	227 098	194 772
Dec 2016	26 199	245 484	140 603
2016	1 462 027	2 423 264	2 313 890