

Development of an integrated cost model for steel production planning

WA Pelser



orcid.org 0000-0002-8433-7844

Thesis submitted in fulfilment of the requirements for the degree
Doctor of Philosophy in Electrical and Electronic Engineering at
the North-West University

Promoter: Dr JH Marais

Graduation ceremony: May 2019

Student number: 22704515

ABSTRACT

Title: Development of an integrated cost model for steel production planning
Author: WA Pelser
Supervisor: Dr JH Marais
School: North-West University, Potchefstroom Campus
Degree: PhD in Electrical and Electronic Engineering

The international steel-manufacturing industry has been referred to as a driving force for industrial development, which is critical to a country's development. This industry is experiencing several challenges due to a reported surplus in production that is flooding the market. An excess supply coupled with high production costs affect the profitability of the steel-manufacturing industry. Research indicates that 20% to 40% of steel production costs originate from energy expenses. Energy cost reduction measures can be used to reduce production costs in steel manufacturing. Cost reduction measures can improve the profitability of the industry and also stimulate the economy.

Multiple existing production planning and energy management approaches aimed at cost reduction were evaluated. It was found that existing approaches lack an integrated solution. A need was identified to develop a new cost model for considering different plant sections, energy sources, and existing solutions and initiatives using an integrated approach.

A new methodology was developed by focusing on the identification, evaluation, comparison, prioritisation, implementation and integration of steel production planning initiatives. The integration aimed to determine the effect that individual initiatives have on one another to prioritise solutions dynamically based on the most beneficial conditions. Theoretically quantified benefits were combined with practical constraints to realise this.

The methodology was verified by the theoretical application thereof on a marginally profitable steelmaking facility. Historical data for a full year was applied to the methodology to evaluate the effect of five identified initiatives, which resulted in an annual potential cost benefit of R11.9 million. This is significantly more than the theoretical benefit of R3.4 million that was obtained using a non-integrated approach. The methodology was validated with a practical application on the same facility. Two of the initiatives were implemented with an estimated annual cost benefit of R13.3 million.

A comparison between the theoretical and practical applications provided a valuable platform for evaluating the methodology. Additionally, extrapolation to the South African steel industry

indicated a potential impact of R60 million per annum. The use of the integrated cost model thus addresses the need to reduce energy costs in steel manufacturing.

Keywords: Steel production planning; integrated cost model; energy cost efficiency; prioritisation model; benefit quantification.

ACKNOWLEDGEMENTS

I would firstly like to thank the Lord, Jesus Christ, for blessing me with the ability and opportunity to do this work.

Also, thank you to the following parties:

- My dearest family (Grandpa Corrie, Dad Johan, Mom Karin, Brother Ernest, and Sister-in-law Soné) for all of the love, support and understanding.
- Dr Marais, Dr Breytenbach and Dr Booysen for their assistance and guidance throughout the study.
- All those involved with the practical application of the model on the steelmaking facility.
- The personnel at the steelmaking facility for the opportunity to work with them.
- My fellow PhD students and colleagues.
- My proofreader, Marike van Rensburg.
- Prof. E.H. Mathews and Prof. M. Kleingeld as well as ETA Operations (Pty) Ltd, Enermanage and its sister companies for the resources, time and financial assistance to complete this study.
- Finally, to all of my friends and family – thank you for understanding when I had to decline an invitation. I hope that we can make up for lost time. A special thanks to the Coertzes, Coetzees, Rautenbachs, Venters, Mienie and Wikus.

TABLE OF CONTENTS

Abstract	ii
Acknowledgements	iv
Table of contents	v
List of figures	vii
List of tables.....	x
List of equations	xii
Nomenclature	xiii
Abbreviations	xiv
Units of measure	xiv
1. Introduction and background	2
1.1. Preamble	2
1.2. Background on steelmaking.....	2
1.3. The need for integrated steel production planning	9
1.4. Novel contributions of the study	16
1.5. Thesis overview	19
2. Steel production planning	22
2.1. Introduction	22
2.2. Overview of production planning	22
2.3. Existing production planning approaches	27
2.4. Initiatives for steel production planning	37
2.5. Implementation, integration and assessment techniques	42
2.6. Conclusion	55
3. Development of an integrated cost model for steel production planning	57
3.1. Introduction	57
3.2. Integrated cost model for steel production planning	57
3.3. Novel contributions of the methodology	76
3.4. Conclusion	79

4. Verification of the integrated cost model	81
4.1. Introduction	81
4.2. Background on the facility	81
4.3. Verification of the methodology	88
4.4. Novel contributions of the theoretical application	115
4.5. Conclusion	117
5. Validation of the integrated cost model	119
5.1. Introduction	119
5.2. Validation of facility results	119
5.3. Discussion of results	142
5.4. Novel contributions of the practical application	147
5.5. Conclusion	148
6. Conclusion and recommendations	150
6.1. Preamble	150
6.2. Overview of the study	150
6.3. Evaluation of the novel contributions	151
6.4. Recommendations for future work	153
6.5. Closure	155
References	156
Appendix A: Steelmaking methods	168
Appendix B: Theoretical evaluation of performance from historical data	172
Appendix C: Description of the properties of steel qualities	189
Appendix D: Energy intensity of steel qualities at ladle furnaces	193
Appendix E: Ladle and crane time loss reduction regression models	195
Appendix F: Variance of apportionment model steel quality properties	197
Appendix G: Primary rolling mill electrical energy intensity	198
Appendix H: Ladle furnace load shifting implementation	200
Appendix I: Hot charging implementation	207
Appendix J: Ladle furnace load shifting monitoring	220
Appendix K: Hot charging monitoring	228

LIST OF FIGURES

Figure 1: Steel production and consumption for major countries and South Africa (2016) [5]	3
Figure 2: Theoretical energy consumption distribution of a steel plant [15, 17].....	6
Figure 3: Different methods for steel production [15]	7
Figure 4: Research objectives linked to the novel contributions	17
Figure 5: Summary of existing solutions discussed in the literature review.....	22
Figure 6: General process for production planning (as adapted from Lin <i>et al.</i> [23]).....	23
Figure 7: ISO 50001 framework (adapted from [80] and [85]).....	46
Figure 8: Example of energy-neutral baseline scaling	54
Figure 9: Example of a regression baseline model [94].....	54
Figure 10: Development of the simplified methodology using existing solution.....	58
Figure 11: Integrated cost model for steel production planning	59
Figure 12: Conceptual overview of production planning relative to different sections	61
Figure 13: Conceptual overview of production planning to be achieved by the model	62
Figure 14: Steps for evaluating a production planning initiative	64
Figure 15: Implementation of the initiatives based on ISO 50001.....	69
Figure 16: Steps for implementing a production planning initiative	70
Figure 17: Integration of multiple production planning initiatives.....	75
Figure 18: Evaluation of novel contributions based on the methodology	77
Figure 19: Basic facility layout for the steelmaking and primary rolling sections of Plant X..	82
Figure 20: Production planning at Plant X	83
Figure 21: Comparison between steelmaking and primary rolling energy cost	85
Figure 22: Steelmaking energy source cost distribution	86
Figure 23: Primary rolling mill energy source cost distribution	87
Figure 24: Theoretical cost benefit of the increased hot charging initiative for 2016	99
Figure 25: Theoretical cost benefit of the ladle furnace load shifting initiative for 2016.....	100
Figure 26: Theoretical cost benefit of the primary rolling mill load shifting initiative for 2016	101
Figure 27: Basic integration of theoretical initiatives (based on Figure 17)	110
Figure 28: Theoretical cost benefit of integrated initiatives for 2016	111
Figure 29: Monthly theoretical cost benefit effect of the integrated approach for 2016	112
Figure 30: Theoretical effect of using an integrated approach.....	113
Figure 31: Theoretical cost benefit distribution of integrated initiatives for 2016	114
Figure 32: Prioritisation frequency of integrated initiatives.....	121
Figure 33: Ladle furnace load shifting Production Route 2 steel qualities reference sheet	124
Figure 34: Ladle furnace load shifting online interface input sample.....	126

Figure 35: TOU wall clock example	127
Figure 36: Ladle furnace load shifting baseline average daily power profiles	129
Figure 37: Example of weekly energy-neutral baseline scaling (7 to 16 July 2017)	131
Figure 38: Practical daily cost benefit of ladle furnace load shifting implementation	132
Figure 39: Practical monthly cost benefit of ladle furnace load shifting implementation	132
Figure 40: Number of data points for different hot charging baseline periods	134
Figure 41: Summary of hot charging baseline regression models	134
Figure 42: Practical daily cost benefit of hot charging implementation	137
Figure 43: Basic integration of practically implemented initiatives (based on Figure 17)	138
Figure 44: Decision-making flow diagram for the practical integration of initiatives	139
Figure 45: Practical daily cost benefit of integrated initiatives	140
Figure 46: Practical monthly cost benefit of ladle furnace load shifting implementation with compensation for integrated effect	141
Figure 47: Practical effect of not using an integrated approach	141
Figure 48: Extrapolated practical daily cost benefit of integrated initiatives	142
Figure 49: Extrapolated practical daily cost benefit of ladle furnace load shifting	143
Figure 50: Extrapolated practical effect of not using an integrated approach	143
Figure 51: Extrapolated practical yearly cost benefit of integrated initiatives	144
Figure 52: Alternative effect of not using an integrated approach	144
Figure 53: Monthly cost benefits of theoretical and practical applications	145
Figure 54: Yearly cost benefits of theoretical and practical applications	146
Figure 55: Different methods for steel production [15] (first presented in Figure 3)	168
Figure 56: Illustrative layout of an EAF	170
Figure 57: Energy consumption of major energy consuming components [14]	171
Figure 58: Regression line for 10% $\pm$ 10% hot charging range	173
Figure 59: Regression line for 30% $\pm$ 10% hot charging range	173
Figure 60: Regression line for 50% $\pm$ 10% hot charging range	174
Figure 61: Regression line for 70% $\pm$ 10% hot charging range	174
Figure 62: Regression line for 90% $\pm$ 10% hot charging range	175
Figure 63: Regression lines for hot charging ranges	175
Figure 64: Effect of hot charging on energy intensity (example for December 2016)	177
Figure 65: Hot charging effect on production and gas consumption	178
Figure 66: Hot charging effect on energy intensity	178
Figure 67: Frequency plot of ladle furnace energy consumption of two steel qualities	179
Figure 68: Frequency plot of energy consumption of different ladle furnaces	180
Figure 69: Energy consumption variation per heating cycle for different production routes	180
Figure 70: Best- and worst-case scenario energy costs for different production routes	181

Figure 71: Frequency plot of BOFs to ladle furnace transfer times	182
Figure 72: Frequency plot of ladle furnace to concast transfer times	182
Figure 73: Frequency plot of casting duration	183
Figure 74: Intensity of gas flow to maintain furnace temperature for steel qualities	185
Figure 75: Example of the effect of steel qualities on average furnace temperature	185
Figure 76: Example of the effect of one steel qualities on average furnace temperature ...	186
Figure 77: Frequency plot of highest and lowest power consuming combinations at the primary rolling mill	187
Figure 78: Highest and lowest electricity cost combinations at the primary rolling mill	187
Figure 79: Ladle furnace-concast transfer time vs temperature reduction regression	195
Figure 80: BOF-concast transfer time vs temperature reduction regression	196
Figure 81: BOF-concast transfer time vs energy consumption regression	196
Figure 82: Furnace 1 [COG] regression model	228
Figure 83: Furnace 2 [COG] regression model	229
Figure 84: 2 Furnace [COG] regression model	229
Figure 85: Furnace 1 [NG] regression model	230
Figure 86: Furnace 2 [NG] regression model	230
Figure 87: 2 Furnace [NG] regression model	231

LIST OF TABLES

Table 1: Summary of literature related to the general steelmaking facility energy initiatives	10
Table 2: Summary of literature related to steel plant production scheduling	12
Table 3: Summary of literature related to scheduling that focus on energy cost efficiency ..	13
Table 4: Summary of literature related to scheduling that focus on production efficiency	14
Table 5: Summary of the literature related to the integration of initiatives.....	15
Table 6: Summary of the literature survey related to energy cost focused production planning	23
Table 7: Summary of the literature survey regarding the identification and prioritisation of initiatives	42
Table 8: Description and allocated values of variables used by Breytenbach [24]	43
Table 9: General energy management literature survey summary	45
Table 10: Energy awareness techniques literature survey summary	49
Table 11: Benefit quantification literature survey summary	51
Table 12: Basic description of identified initiatives.....	63
Table 13: Value allocation of evaluation steps for initiative ranking	68
Table 14: Suggested baseline methodologies for identified initiatives	74
Table 15: Status overview for identified initiatives	90
Table 16: Required historical data for identified initiatives	92
Table 17: Data availability overview for identified initiatives	93
Table 18: Summary of theoretical evaluation of historical performance (summary of Appendix B)	94
Table 19: Historical performance overview for identified initiatives	95
Table 20: Practical constraints overview for identified initiatives.....	95
Table 21: Potential benefit overview for identified initiatives	98
Table 22: Comparison of evaluated initiatives	102
Table 23: Summary of initiative evaluation	120
Table 24: Initiative ranking based on evaluation of identified initiatives	120
Table 25: Practical implementation dates of initiatives	122
Table 26: Hot charging condonable profiles	133
Table 27: Hot charging baseline regression model characterisation.....	135
Table 28: Summary of key indicators for hot charging baseline.....	135
Table 29: Summary of hot charging practical application results	136
Table 30: Primary rolling mill furnace production and hot charging.....	172
Table 31: Estimated gas reduction for hot charging percentage ranges	176
Table 32: Theoretical cost benefit of hot charging percentage ranges.....	176
Table 33: Description of the properties of the steel qualities.....	189

Table 34: Energy intensity of Production Route 2 steel qualities at the ladle furnaces.....	193
Table 35: Energy intensity of Production Route 3 steel qualities at the ladle furnaces.....	194
Table 36: Variance in the properties of the apportionment model steel qualities	197
Table 37: Electrical energy intensities for the primary rolling mill.....	198
Table 38: Basic list of tasks conducted during ladle furnace load shifting implementation.	206
Table 39: Basic list of tasks conducted during hot charging initiative implementation.....	219

LIST OF EQUATIONS

Equation 1: Initiative ranking calculation for prioritisation (adapted from Breytenbach [24]).	43
Equation 2: Calculation of service level adjustment for energy-neutral scaling [94]	53
Equation 3: Adjusted baseline using service level adjustment [94]	53
Equation 4: Straight line formula used in the regression model example [84]	55
Equation 5: Calculation of the impact of an initiative [94].....	55
Equation 6: Initiative ranking calculation for the comparison of initiatives	69
Equation 7: Baseline adjustment for weekly energy-neutral scaling	130
Equation 8: Daily cost saving calculation for ladle furnace load shifting	130
Equation 9: Straight line formula (first presented in Equation 4)	176

NOMENCLATURE

Billet	For the case study facility, a billet refers to a steel slab rolled by the primary rolling mill.
Bloom	For the case study facility, a bloom refers to a steel slab that has already been casted by the continuous caster, but has not yet been rolled by the primary rolling mill.
Cast	For the case study facility, a cast is a ladle of liquid steel that is casted continuously.
Energy	Kilowatt-hour is a measure of energy consumed. This can be calculated from the product of power (in kW) and the time period for which the power was consumed (in hours).
Ladle	A ladle is a large vessel used to transport and pour molten metal.
Ladle furnace	A ladle furnace uses a three-electrode electric furnace, where liquid steel is further refined according to its steel quality requirements, to ensure that the temperatures are at the desired levels for continuous casting.
Power	Kilowatt is a measure of power, and is defined as the energy consumption of 1 000 joules for a period of 1 second ($1 \text{ kW} = 1\,000 \text{ J/s}$).
Profile	For the case study facility, a profile refers to the size and shape in which a steel slab is rolled.
Production route	The production route used to achieve the required steel quality depending on the required sections on the facility.
Sequence	A sequence consists of several consecutive ladles casted at the continuous caster.
Steel quality	For the case study facility, steel quality refers to the specific composition requirements of the steel.
Time of use	Varying electricity tariffs depending on the time of day.
Tonne	1 tonne is equal to 1 000 kg (approximately 2 205 pounds). This is often referred to as a metric ton in American English due to the different meaning of ton.
Torpedo	For the case study facility, a torpedo is used to transport liquid iron from the blast furnace to the steel plant.
Tundish	For the case study facility, a tundish is used to distribute liquid steel from a single ladle into several strings when casting blooms at the continuous caster.

ABBREVIATIONS

BF-BOF	blast furnace – basic oxygen furnace
BOF	basic oxygen furnace
COG	coke oven gas
concast	continuous caster
DRI	direct reduced iron
EAf	electric arc furnace
GDP	gross domestic product
ISO	International Organisation for Standardization
M&V	measurement and verification
PDCA	plan-do-check-act
R ²	coefficient of determination
TOU	time of use
US	United States

UNITS OF MEASURE

°C	degree Celsius
GJ	gigajoule
GJ/day	gigajoule per day
GJ/t	gigajoule per tonne
kW	kilowatt
kWh/heat	kilowatt-hour per heating cycle
kWh/t	kilowatt-hour per tonne
m ³ /h	cubic metre per hour
m ³ /h/°C	cubic metre per hour per degree Celsius
min	minute
MW	megawatt
MWh	megawatt-hour
R	rand (South African)
R/day	rand per day
t	tonne (metric ton)
t/day	tonne per day
TJ	terajoule

Chapter 1: Introduction and background

This chapter introduces the reader to the purpose of the study by providing the necessary background information. Existing research with relevance to the thesis is briefly reviewed.

The shortcomings of the research are then used to formulate the objectives and novel contributions of this study.

1. INTRODUCTION AND BACKGROUND

1.1. PREAMBLE

The first chapter of this thesis introduces the reader to the study by discussing the necessary background information. The background information includes a review of existing research in the field of production planning and energy management in steelmaking facilities. Shortcomings of existing research are analysed to identify the need for the study and formulate the research objectives from which the novel contributions are formulated.

1.2. BACKGROUND ON STEELMAKING

1.2.1. THE INTERNATIONAL STEEL INDUSTRY

The international steel-manufacturing industry is experiencing challenges due to surplus production flooding the market [1, 2, 3, 4].¹ The surplus reportedly originated due to a decline in Chinese steel demand, which led to China exporting more steel to the rest of the world.² This creates a problem for other steel manufacturers as the Chinese government provides subsidies for steel manufacturing.^{3,4} In various countries, steel imported from China is significantly cheaper than steel produced by local steel producers. Even though this can be considered as an advantage to the end consumer, it is a disadvantage for steel producers in affected countries such as South Africa.

In 2016, 1 630 million tonnes of steel was produced worldwide, but only 1 515 million tonnes was consumed, thereby supporting the claim of a flooded market. In the same year, South Africa produced 6.1 million tonnes of the world's steel, but only consumed 5 million tonnes thereof [5]. Figure 1 summarises and compares South Africa's steel production and consumption with that of the major steel-producing countries. The figure was compiled with data obtained from the World Steel Association [5]. The comparison of Figure 1a with Figure 1b shows that China produced 4.6% more steel than they consumed. This is approximately 75 million tonnes – more than 12 times the amount of steel produced by South Africa.

News articles are referenced as footnotes:

¹ S. Njobeni, "Duty to protect SA steel industry," *BusinessReport*, 9 May 2017.

² L. Prinsloo and K. Crowley, "ArcelorMittal SA plans to raise R3.5bn in debt," *Fin24*, 6 April 2017.

³ S. Nkabinde, "Dumping, China, and ArcelorMittal," *Moneyweb*, 20 July 2015.

⁴ R. Wilkinson, "Import prices on steel not the best solution," *Creamer Media's Engineering News*, 1 July 2016.

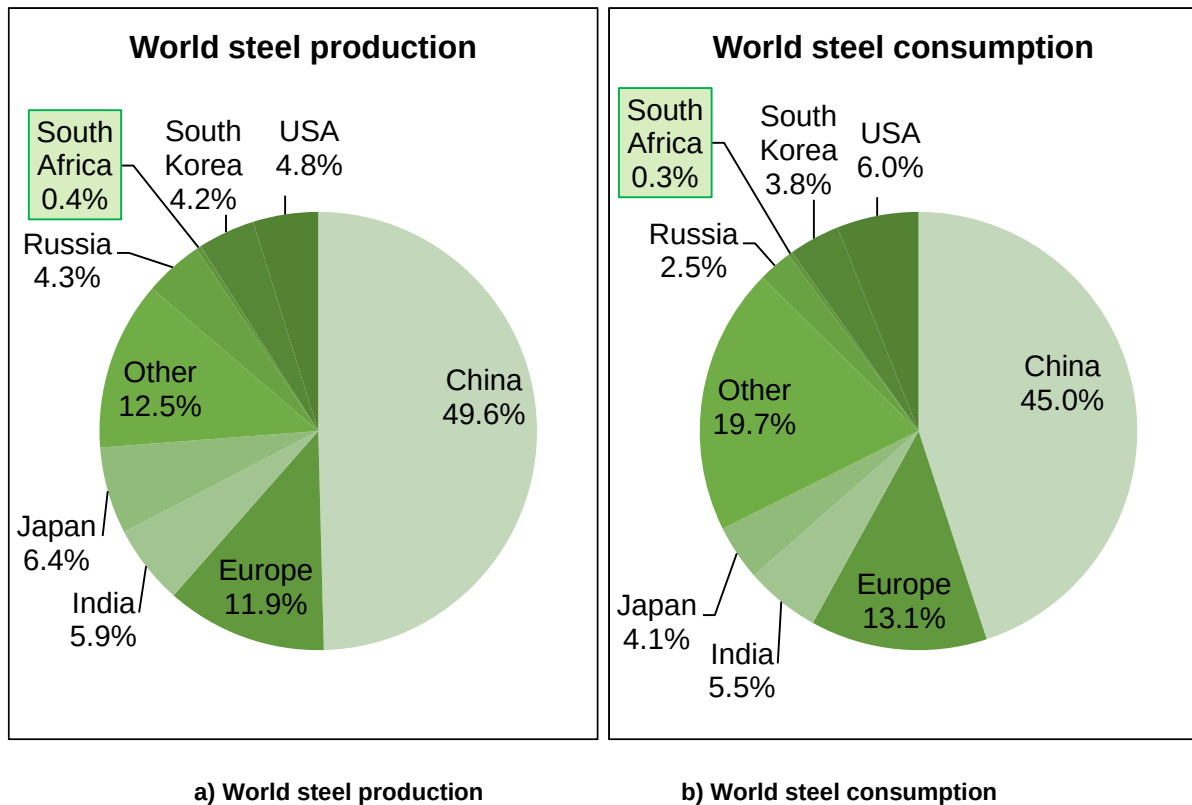


Figure 1: Steel production and consumption for major countries and South Africa (2016) [5]

1.2.2. THE SOUTH AFRICAN STEELMAKING ENVIRONMENT

South Africa is considered to be a minor role player in the steel industry and is therefore vulnerable to decisions in other markets [6]. Apart from the challenges faced internationally due to an oversupplied market, South African steel producers also have to manage additional problematic factors. These factors include the increasing cost of raw materials, higher electricity tariffs, irregular wage inflations, and a hike in transportation costs [6, 7]. These factors mostly result from exchange rate volatility and a weakening economy in the country.⁵ Such challenges are reported to have reduced the country's steel production capacity from 9.7 million tonnes in 2006 to 6.6 million tonnes in 2014 [8].

As a result, several South African steelmaking facilities have become marginally profitable [6]. One of the consequences of these challenges is conflict among workers over jobs.⁶ Another concern is that using imported steel is often a more affordable option for consumers rather than purchasing steel from local producers. A partial solution to this problem was the increased import duties for selected steel products by the Trade Administration Commission of South Africa [4]. It is, however, believed that this is not a sustainable solution, as it leads to higher

⁵ T. Heiberg, "ArcelorMittal South Africa loss deepens," *Moneyweb*, 27 July 2017.

⁶ S. Ashman, "The crises in steel and mining and what they mean for the South African economy," *Amandla!*, no. 49/50, December 2016.

input costs for local businesses due to more expensive steel imports. This, in turn, causes an increase in the prices of goods purchased by the end consumer.⁷

The iron and steel industry is considered an essential sector for the economic and industrial development of a country and has been referred to as a driving force for industrial development [9]. The industry provides the most important materials for use in other industries of the economy and plays a vital role in the development of a country [9]. Effective production planning is considered to be a very important factor in steelmaking due to the high capital and energy intensity of such facilities [9]. This highlights the importance of effective production planning at these facilities and the focus that has to be placed on improved energy intensity.

Research by Dondofema, Matope and Akdogan [8] indicated that limited research on improved production processes has been published in South Africa (only five publications by the South African Institute of Industrial Engineering). Dondofema *et al.* [8] also referred to the review of South African industrial engineering by Van Dyk [10], which indicated that few industrial engineers are employed by the iron and steel industry in South Africa. This serves as an indication of the lack of focus on production optimisation in steel-manufacturing facilities in the country, which could be a contributing factor for the poor performance of the industry.

The steel industry in South Africa has been reported to directly represent 1.5% of the gross domestic product (GDP). The indirect influence of this industry is about 15% of the GDP due to the steel industry supporting several sections of the economy. Furthermore, the steel industry also indirectly employs about 8 million people [4]. This serves as an indication that the steel industry plays a vital role in the situation of the country's economy; therefore, it is critical to focus on the efficiency thereof.

At the time of publication, ArcelorMittal South Africa is reported to be the largest iron- and steel-producing company in the country with an annual production capacity of 6.1 million tonnes of steel [8, 11]. Other contributors to the industry in the country to date are reported to be Cape Gate (Pty) Ltd, Columbus Stainless (Pty) Ltd, Scaw Metals Group, South Africa Steelworks, and Unica Iron and Steel (Pty) Ltd. [8]. Several steel producers in South Africa have already stopped with operations; it is reported that the harsh conditions pose a threat to the continued existence of the industry in the country [8].

A study by Deloitte [12] evaluated the future effect that further rising electricity prices could have on various economic sectors in South Africa. This evaluation analysed the effect that the 78% increase in electricity prices in the country between 2008 and 2011 had on different

⁷ R. Wilkinson, "Import prices on steel not the best solution," *Creamer Media's Engineering News*, 1 July 2016.

sectors, and made assumptions on the possible effect of future increases [12]. An important finding from this study is that low energy prices lead to poor decision-making and misallocation of economic resources [12]. This finding is not only relevant to electricity prices but can also be expanded to other energy sources. This highlights the historical lack of focus on energy efficiency in the country's operations.

A study by Kohler [13] in 2006 indicated that South Africa had a competitive advantage at that time due to the low cost of energy. Kohler [13] indicated that low-cost energy was inefficient as it restricted the focus on saving energy costs by using energy efficiency measures. The increased prices of energy sources since then had a negative effect on this competitive advantage, which is indicated by the electricity price increases that followed and the evaluation of the effect thereof by Deloitte [12].

The analysis done by Deloitte [12] identified the iron and steel industry as the second-largest consumer of electrical energy in South Africa between 1993 and 2006. A survey among employees in the mining, manufacturing and metal-manufacturing sectors indicated that the metal-manufacturing industry managed the least gains in electricity efficiency following the price increases [12]. This indicates the resistance towards innovation and improvements in this sector, as well as the limited opportunities that exist. It was further seen that the electricity intensity of the basic metals sector in South Africa is eight times less efficient than the electric intensity in countries in the Organisation for Economic Co-operation and Development (OECD) [12].

The effect of the 24.8% electricity price increase from 2010/11 to 2012/13 in South Africa was also assessed based on different factors for the various industries. It was found that this increase had the largest effect on the production output of the iron and steel industry, with a reduction of 5.3% [12]. This increase was reported to also result in a decrease in employment of 4.6% [12]. Within the mining sector it was found that iron mines are also one of the most vulnerable sectors to electricity price increases; therefore, directly affecting the raw material input costs for steelmaking [12]. It can be assumed that the increase in general energy source prices has a similar effect on the iron and steel industry.

1.2.3. ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

Steel-manufacturing facilities have been reported to be responsible for 18% of industrial energy consumption in the world [14]. Further research indicates that between 20% and 40% of steel production costs originate from energy expenses [15, 16]. It is also reported that, in some cases, energy efficiency improvements of up to 60% have been achieved compared with plants' original states [15]. This highlights the effect that technology can have on a steel-

manufacturing facility. It is expected that older outdated facilities will not be as efficient as newly constructed facilities with the latest technology. It is clear from this information that energy efficiency improvement should be an area of focus for such facilities.

Figure 2 presents the theoretical energy source consumption distribution of a steelmaking facility, as adapted from data made available by the World Steel Association [15, 17]. Coal contributes half of the energy consumed at an iron- and steelmaking facility, which is followed by electrical energy (35%) and natural gas (5%). The remainder of the energy sources accounts for 10% of the total energy consumption [15]. An additional energy source is by-product gases, which can be used directly in processes or used to generate electricity [15].

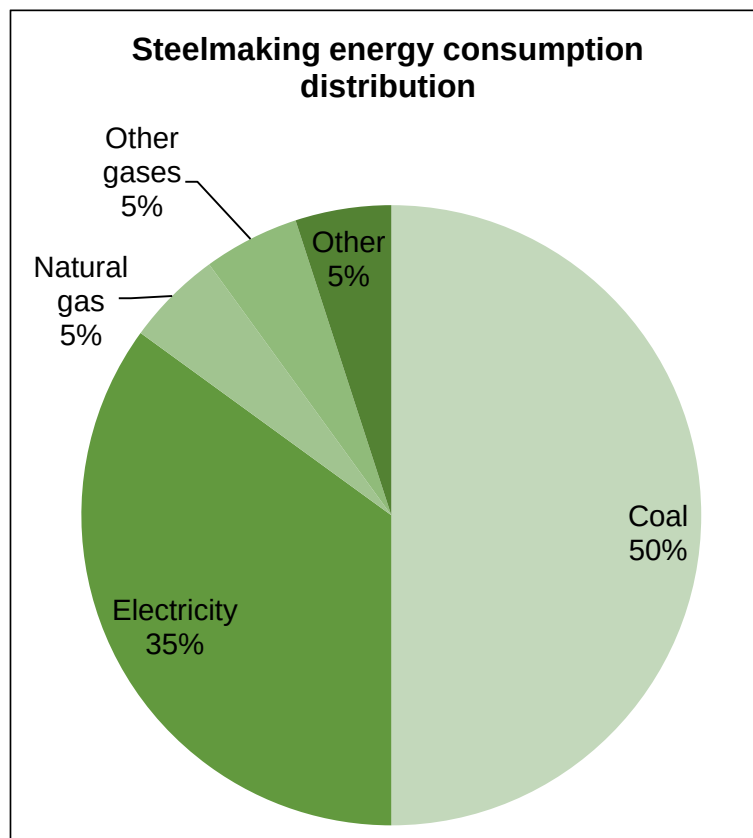


Figure 2: Theoretical energy consumption distribution of a steel plant [15, 17]

From this information, it is clear that the major energy sources on a steelmaking facility are coal, electricity and gas (both natural gas and by-product gases). The energy sources, however, also depend on the type of steel-manufacturing process that is used [14]. Apart from the continued rising cost of energy sources, the public perception of energy efficiency, carbon footprints and the ecological effect that companies have are also motivation for industries to focus on energy efficiency [18, 19, 20]. The increasing risk for possible taxes to be paid on carbon emissions directly links this public perception to a cost factor for companies; therefore, further motivating an increased focus on energy efficient behaviour [20].

A method for improved energy efficiency that has obtained a great deal of attention in recent decades is reported to be short-term production planning [21, 22]. Short-term production planning is described as an *enabler* for improved energy consumption and the stabilisation of the power grid [21]. The basic concept is to consider energy consumption as an input factor for production planning, which makes it possible to forecast and improve consumption trends. A very important factor is to be able to predict the effect that a change in the production schedule will have on energy costs [21]. Production planning is typically associated with industrial processes, such as those used in the steelmaking industry.

1.2.4. STEELMAKING FACILITIES

Overview of steel production

There are different processes that can be used to manufacture steel. The main methods are referred to as the blast furnace–basic oxygen furnace (BF-BOF) and electric arc furnace (EAF) methods [14, 15]. About 25% of steel is produced using the EAF method, while the other 75% is produced using the BF-BOF method [15]. Another steelmaking technology, referred to as the open hearth furnace, accounts for about 0.5% of global steel production [14]. This process is not widely used due to its high energy intensity and the economic and environmental disadvantages it entails [14].

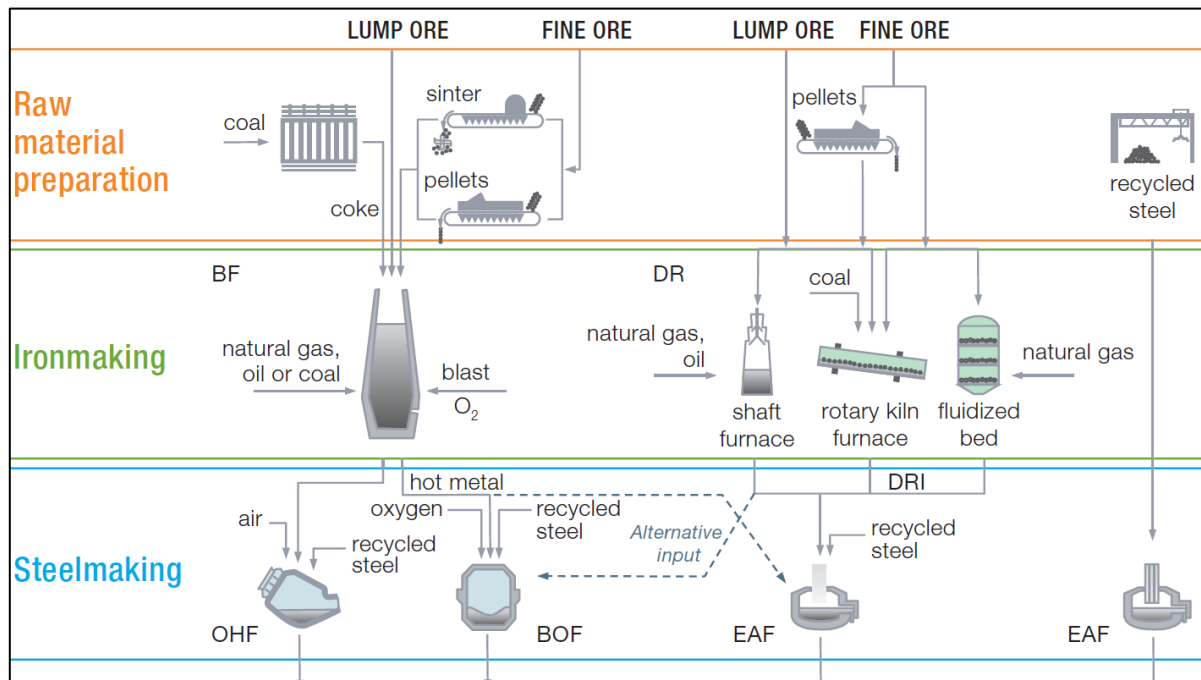


Figure 3: Different methods for steel production [15]

BF: blast furnace; BOF: basic oxygen furnace; DR: direct reduction; DRI: direct reduced iron; EAF: electric arc furnace; OHF: open hearth furnace

A basic overview of the different steel production methods is provided in Figure 3 [15]. The reader is referred to Appendix A for a detailed discussion of the different steel production methods. The most important factor to note for this study is that the EAF method is a batch process, while the BF-BOF production method is more of a continuous production process.

Steel production planning

For this study, the steelmaking and primary rolling sections have been identified as areas where opportunities for improved production planning exist. The boundary excludes the production of iron and only focuses on the steps labelled as *steelmaking* in Figure 3, up to the primary rolling mill. The main production planning functions for this boundary are scheduling steel to be casted, and minimising the time spent between casting and reheating of furnaces. This study focuses specifically on the production planning challenges of this boundary.

Production planning is described to be most commonly performed manually by experienced production planners [21]. The problem is, however, that the complexity of production planning is increasing continuously due to higher production requirements, a wider variety of products, unstable orders from customers, and increased pressure to reduce the cost of production and energy [21]. It is vital for production planners to be receptive to new approaches and tools that can be used to assist with compiling production schedules. Resistance towards change and technological solutions further complicate the adaption towards the challenges in production planning processes [12].

According to research conducted by Lin *et al.* [23], production planners rarely consider the integration between continuous casting and rolling mills on a steelmaking facility. A gap was identified in the integration of these sections in terms of production planning [23]. Practical uncertainties limiting this integration, as listed by Lin *et al.* [23], include:

- Productivity uncertainty;
- Processing time uncertainty;
- Production lead time uncertainty;
- Steel quality uncertainty;
- Changes to steel qualities; and
- Failure of production equipment.

There is therefore a need for solutions addressing these uncertainties. Advantages of implementing such solutions are improvements in terms of production plan quality, and the improvement of the profitability of the facility [23].

1.3. THE NEED FOR INTEGRATED STEEL PRODUCTION PLANNING

1.3.1. PROBLEM STATEMENT

A surplus in steel production worldwide along with challenging conditions in the South African economic environment place the country's steel producers under pressure. Additionally, increasing energy costs and an increased focus on companies' environmental footprints highlight energy cost efficiency as a critical focus area. There is also a lack of industrial engineering influences on South African steelmaking facilities, which indicates an area for possible improvement. The steelmaking and primary rolling sections of the steelmaking industry were identified as possible areas for production planning improvements with the aim being to reduce energy cost. The focus is also placed on marginally profitable facilities.

There is therefore a need for improved steel production planning with the aim of reducing the cost of steel production. This will be achieved by integrating several energy management techniques and production planning initiatives aimed at cost reduction. The need for an integrated approach is due to the complexity and inter-active effects of the steel production planning process.

New challenges due to the competitive market and changing needs of customers lead to the increased complexity of production planning tasks. Production planners are expected to adapt to these challenges, which is often a troublesome situation as they do not have the required assistive tools. Resistance towards change and technological solutions also restrict the adaption of these challenges. The study therefore focuses on using an International Organisation for Standardization (ISO) 50001-based implementation strategy rather than using automated solutions to address the unique challenges of marginally profitable facilities.

1.3.2. SUMMARY OF EXISTING PRODUCTION PLANNING APPROACHES

Preamble

This sub-section summarises the existing studies used for energy efficiency and production planning that are relevant to the identified problem. The investigated research is summarised in tables for fields of study relevant to this thesis, which is then used to summarise the shortcomings of the existing methods. A more detailed discussion of the most relevant studies are provided in the literature survey of the next chapter. The shortcomings are used to state the objectives that need to be addressed by the discussion in this thesis. The information provided in this section is relevant to Section 1.4, which formulates the novel contributions. The criteria used to evaluate the existing research are:

- The study focuses on the steel industry;
- The study focuses on production planning;
- The main focus of the study is on energy cost efficiency;
- The main focus of the study is on production cost efficiency;
- The study integrates different sections on the same facility;
- The development of the solution integrates existing solutions;
- The solution integrates production and energy aspects on the facility;
- The study prioritises the order in which to implement initiatives;
- The study dynamically prioritises the implemented initiatives;
- The solution is practically implemented on a facility; and
- The application of the study is on a South African case study.

General steel production energy management

Overview

This discussion evaluates existing methods for steel production energy management relevant to this thesis. This will serve as an indication of how such initiatives in this industry should be approached, and what has already been done. It is then highlighted how this thesis addresses the shortcomings of existing research. The evaluation in Table 1 uses the listed criteria to determine the relevance of the identified studies.

Table 1: Summary of literature related to the general steelmaking facility energy initiatives

Author	Criteria										
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility	Application on a South African case study
Breytenbach [24]	✓		✓		✓			✓		✓	✓
Dondofema <i>et al.</i> [8]	✓	✓									✓
He and Wang [14]	✓	✓	✓							✓	
National Cleaner Production Centre of South Africa [25]	✓	✓	✓							✓	✓

Author	Criteria										
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility	Application on a South African case study
Remus <i>et al.</i> [26]	✓		✓								
Shen <i>et al.</i> [27]	✓		✓	✓		✓	✓				
Worrel <i>et al.</i> [28]	✓	✓	✓	✓							

Summary

The existing research does not focus extensively on developing a methodology to improve production planning for South African steelmaking facilities. Studies that are focused in South Africa mostly consider energy management strategies or they fall beyond the boundary identified for this thesis.

Steel production planning methods

Overview

Several studies focusing on production planning in the steelmaking industry were evaluated. Most studies use automated solutions and complex mathematical models rather than the ISO 50001-based implementation strategy used in this thesis [29, 30, 31, 32]. The models were not applied to South African facilities, and technological and capital constraints were not such major role players. The most relevant of these studies is the optimisation of production schedules in a steel production system developed by Karwat [32]. The evaluation in Table 2 uses the listed criteria to determine the relevance of the identified studies.

Table 2: Summary of literature related to steel plant production scheduling

Author	Criteria										
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility	Application on a South African case study
Chakravarty, Das and Singh [33]	✓	✓	✓	✓			✓			✓	
Dao-fei, Zhong and Xiao-qiang [34]	✓	✓		✓					✓		
Karwat [32]	✓	✓		✓						✓	
Lin <i>et al.</i> [23]	✓	✓		✓	✓					✓	
Mattik, Amorim and Gunther [35]	✓	✓	✓		✓		✓				
Merkert <i>et al.</i> [21]	✓	✓	✓	✓		✓			✓	✓	
NEDO [36]	✓	✓	✓	✓							
PSI Metals Planning [37]	✓	✓	✓	✓						✓	
Xu <i>et al.</i> [38]	✓	✓	✓		✓					✓	

Summary

In general, the research for production planning on these facilities does not integrate different initiatives. The solutions mainly focus on production without integrating energy cost efficiency. The studies provide valuable guidelines for approaches toward steel production planning, but contain important differences from the problem addressed by this thesis. Several of the methods are also conceptual and do not focus on the practical implementation thereof. The results are more idealistic than realistic, and do not assess practical constraints. The facilities that these studies focus on are technologically advanced, and the studies do not deal with resistant personnel who oppose the implementation of automated solutions at marginally profitable facilities.

Production planning for energy cost reduction

Overview

Ample work has been done in various industries that used production planning to improve energy cost efficiency. The most relevant of these studies are briefly discussed to indicate that

the concept is viable, but that existing studies lack certain aspects addressed by this study. These studies are used as an indication of which aspects can be of guidance for steel production planning to improve the focus on energy cost efficiency. The studies are evaluated in Table 3 based on the listed criteria.

Table 3: Summary of literature related to scheduling that focus on energy cost efficiency

Author	Criteria										
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility	Application on a South African case study
Gahm <i>et al.</i> [39]		✓	✓								
Gong <i>et al.</i> [40]		✓	✓			✓				✓	
Hadera <i>et al.</i> [41]	✓	✓	✓							✓	
Hamer [42]		✓	✓			✓				✓	✓
Lu <i>et al.</i> [43]	✓	✓	✓								
Maneschijn [44]		✓	✓			✓				✓	✓
Nolde and Morari [45]	✓	✓	✓								
Rager, Gahm and Denz [18]		✓	✓							✓	
Swanepoel <i>et al.</i> [46]		✓	✓						✓	✓	✓
Yuan-yaun, Ying-lei and Shi-xin [47]	✓	✓	✓								

Summary

From this survey, a few relevant studies considering the concept of energy efficiency as part of the focus when performing production planning were evaluated. It is seen that the concept is becoming more important due to various factors, and that it is possible to achieve cost savings by considering energy consumption and cost as part of production planning. A shortcoming of this research is, however, the lack of applications in steelmaking. These solutions also only focus on improved energy efficiency within certain production requirements, and do not at the same time integrate the improvement of production efficiency. These shortcomings are addressed by the solution developed in this thesis.

Production planning for production cost reduction

Overview

A shortcoming of the previously discussed literature was the lack of integration between production efficiency and energy efficiency during production planning. Existing work that focuses on production efficiency when performing production scheduling is considered in this discussion. A significant amount of work in various industries has been done on this topic, and only a few research studies relevant to this thesis are discussed. Table 4 evaluates the studies relevant to the listed criteria.

Table 4: Summary of literature related to scheduling that focus on production efficiency

Author	Criteria										
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility	Application on a South African case study
Biondi, Sand and Harjunkoski [48]	✓	✓		✓						✓	
Liu <i>et al.</i> [49]	✓	✓		✓							
Lochmüller and Schembecker [50]		✓		✓						✓	
Long <i>et al.</i> [51]	✓	✓		✓	✓						
Moshidi [52]		✓		✓							✓
Tu, Luo and Chai [53]	✓	✓		✓							

Summary

The studies evaluated in this sub-section indicate the importance of proper production planning, and that it has a positive effect on production efficiency. The study by Lochmüller and Schembecker [50] considered the optimisation of batch production plants, and the importance of using available equipment capacities. This study, however, was conducted in a different industry than steelmaking.

The research discussed by Biondi *et al.* [48] focused on improved coordination between production and maintenance scheduling with the purpose of increased equipment lifetimes.

This study used aspects of energy awareness approaches, but was implemented on an EAF steelmaking facility.

Another study that was considered was the business administration research done by Moshidi [52] to determine the functions of maintenance planners at a South African steelmaking facility. This provided background to the steelmaking environment in the country, and suggested guidelines when approaching its planning functions. Even though a specific solution was not developed, the provided guideline based on the relevant research is of high value for the development of a solution in this thesis. In general, the research lacked applications for a BF-BOF steelmaking facility, and no focus was placed on energy efficiency.

Integration of solutions

Overview

The last major focus area for the evaluation of existing studies is the integration of solutions. Various studies using integration techniques are evaluated at the hand of the listed criteria, as summarised in Table 5.

Table 5: Summary of the literature related to the integration of initiatives

Author	Criteria									
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility
David, Goldblatt and Zhang [54]	✓			✓	✓	✓				✓
Dias and Marianthi [55]		✓		✓		✓				
Gajic <i>et al.</i> [56]	✓	✓	✓		✓	✓	✓			✓
Li and Ierapetritou [57]		✓		✓	✓					
Marais [58]			✓		✓	✓		✓		✓
Shah and Ierapetritou [59]		✓		✓	✓					
Zhao, Grossmann and Tang [60]	✓	✓	✓			✓	✓			

Summary

These studies indicate the benefits of using an integrated approach as part of the solution. Integrating existing solutions ensures that the benefit obtained from the implementation is optimal, while integrating different sections ensures that the interactive effects of sections are accounted for. Additionally, integrating production and energy cost benefits ensures that one aspect is not neglected to compensate for another. These studies were, however, not applicable to steel production planning using the BF-BOF production method, and had limited practical applications. Most studies were also not focused on South African case studies, and resultantly neglected some of the unique challenges addressed by this thesis.

1.3.3. RESEARCH OBJECTIVES

The main objective of this thesis is developing an integrated cost model for steel production planning, and applying it to a marginally profitable facility as a case study. This model will reduce cost by identifying, evaluating, comparing, prioritising, implementing and integrating production planning initiatives. The research objectives to achieve this are listed below:

- Assess, adapt and combine existing initiatives and generic methods;
- Evaluate the theoretical value of possible solutions;
- Compare and prioritise integrated initiatives;
- Reduce cost of steel production using minimum capital;
- Develop an integrated solution; and
- Implement practically on steel production planning.

1.4. NOVEL CONTRIBUTIONS OF THE STUDY

The thesis contributes four novel aspects that are formulated based on the shortcomings identified in Section 1.3. The research objectives listed in Section 1.3.3 are linked to the novel contributions in Figure 4. Each novel contribution is discussed in more detail in the remainder of this section.

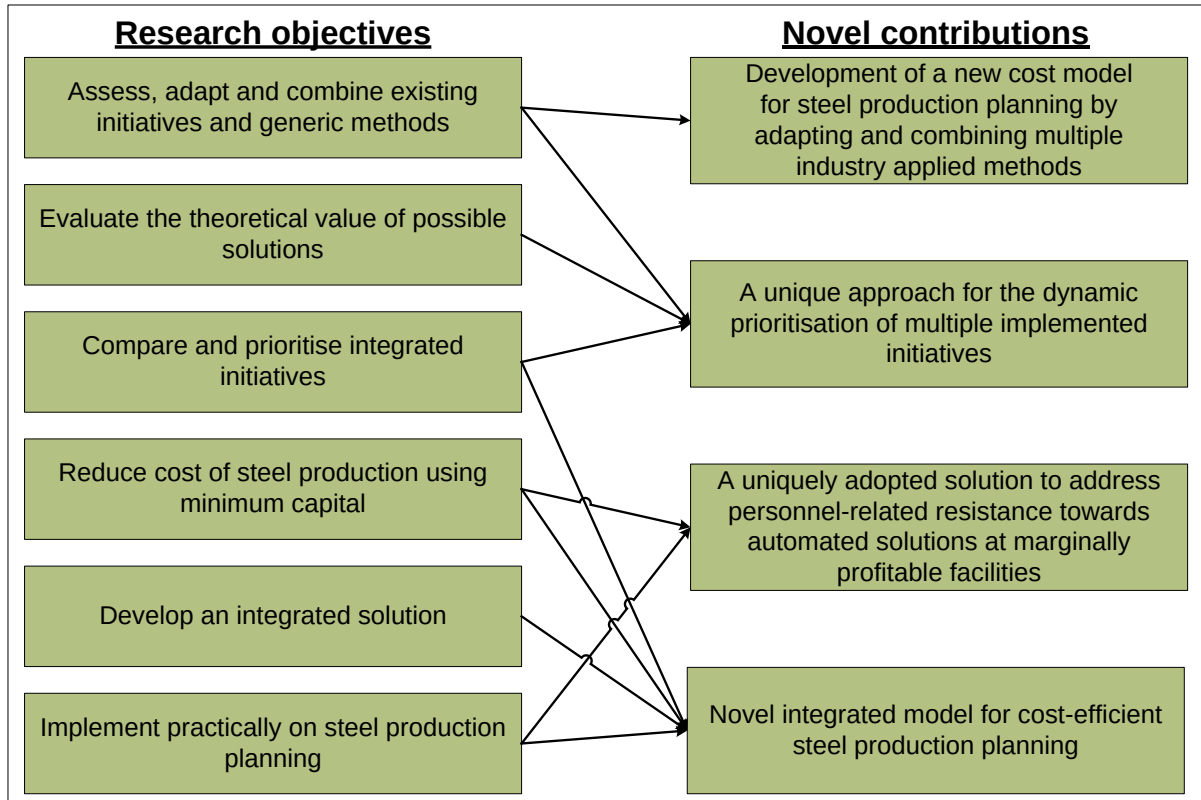


Figure 4: Research objectives linked to the novel contributions

Contribution 1:

*Development of a **new cost model** for steel production planning by **adapting and combining multiple** industry applied methods*

- Research provides information for many existing production planning methods in different industries.
- Focus is typically placed on specific individual solutions rather than using an integrated approach.
- The problem is that initiatives are considered in isolation, and often only one initiative is implemented on a facility.
- Valuable aspects of different existing methods are usually not combined to increase benefits.
- This study solves these shortcomings by adapting and combining multiple methods to develop a new cost model.
- This new cost model adapts and combines multiple initiatives for implementation on a single steelmaking facility.

Contribution 2:

A unique approach for the dynamic prioritisation of multiple implemented initiatives

- Energy cost and production are rarely considered holistically in steel production planning decision-making.
- Existing solutions often use complex mathematical models and algorithms.
- The problem is that site personnel do not always have the time or skills necessary to implement such methods and often discard them.
- Decision-making processes are usually static even though production planning inputs change dynamically.
- A dynamic prioritisation approach focusing on simplified benefit quantification is therefore used to address this problem.

Contribution 3:

A uniquely adopted solution to address personnel-related resistance towards automated solutions at marginally profitable facilities

- Existing methods are mostly implemented on steelmaking facilities in majority role player countries in the steelmaking industry.
- The fragile conditions of marginally profitable facilities lead to resistance toward the implementation of new initiatives.
- Job insecurity in challenging conditions leads to resistance towards automated solutions.
- The problem is that existing methods do not account for these challenges.
- An ISO 50001-based implementation strategy is uniquely adopted and incorporated in the solution to address such practical constraints.
- The practical implementation of the model on a facility facing these challenges presents valuable results for future applications.

Contribution 4:

Novel integrated model for cost-efficient steel production planning

- Several methods for production planning exist in different industries with the purpose of improving either energy or production efficiency.
- Researchers have looked into various options for both technological and organisational improvements.

- Numerous studies have been done on individual interventions to improve the energy efficiency of the steelmaking industry.
- Production planning initiatives in general do not consider integrating several aspects.
- Individually developed solutions have to be integrated into a single approach.
- The thesis develops a cost model using a novel approach to identify, evaluate, compare, prioritise, implement and integrate production planning concepts.

1.5. THESIS OVERVIEW

Chapter 1

The first chapter of this thesis provided the reader with critical background information surrounding the steelmaking industry and its significance in a country such as South Africa. This helps the reader to understand the problem that this study aims to address. Existing research regarding steel production planning relevant to this thesis was evaluated, and the shortcomings thereof were highlighted. Based on these shortcomings, the research objectives were summarised, and the novel contributions of the study were formulated and discussed.

Chapter 2

The second chapter of the study will consist of a literature study. This will focus on a more detailed discussion of the existing solutions evaluated in Chapter 1, and existing solutions/tools that will be used to develop the methodology. This will provide a better understanding of production planning. As a large focus of the study is on adapting and integrating existing production planning initiatives, several such initiatives will be discussed. This will serve as the literature review for the identification of initiatives in the methodology, and will be relevant again later in the thesis.

Chapter 3

In this chapter, a methodology will be developed to solve the problem stated in Chapter 1 by using the existing solutions discussed in Chapter 2. This methodology will focus on addressing the research objectives by reducing the cost of steel production planning. This will serve as the adaption of existing methods and the integration thereof to develop a new cost model for use in steel production planning.

Chapter 4

This chapter will focus on verifying the developed methodology. This will be done by theoretically applying the developed cost model using data from a marginally profitable

steelmaking facility using the BF-BOF production method. This will verify that the methodology can address the identified problem from a theoretical point of view.

Chapter 5

This chapter will validate the methodology by practically applying the developed cost model on the case study facility. The results will be extrapolated and discussed using the theoretical application of Chapter 4. This provides a valuable platform to make recommendations for the methodology based on the different outcomes of the theoretical and practical applications.

Chapter 6

The last chapter of the thesis will conclude the study. The research objectives will be evaluated to indicate how they were addressed by the study, and the success of the developed methodology will be evaluated. Recommendations for future work will also be discussed.

Chapter 2: Literature review

The reader is provided with a review of relevant existing research. The main focus is on literature that can be used as part of the solution for the identified problem.

2. STEEL PRODUCTION PLANNING

2.1. INTRODUCTION

The literature review starts with a brief overview of production planning and its functions, which provides the reader with a better understanding of the critical role that production planning fulfils in steel production. A detailed discussion of the most relevant existing research evaluated in Chapter 1 is then provided. Several steel production planning energy cost saving initiatives are identified and discussed. Lastly, existing solutions to be used in the development of the integrated cost model are provided. The areas of focus for the literature review of existing solutions to be used as part of the methodology are summarised in Figure 5.

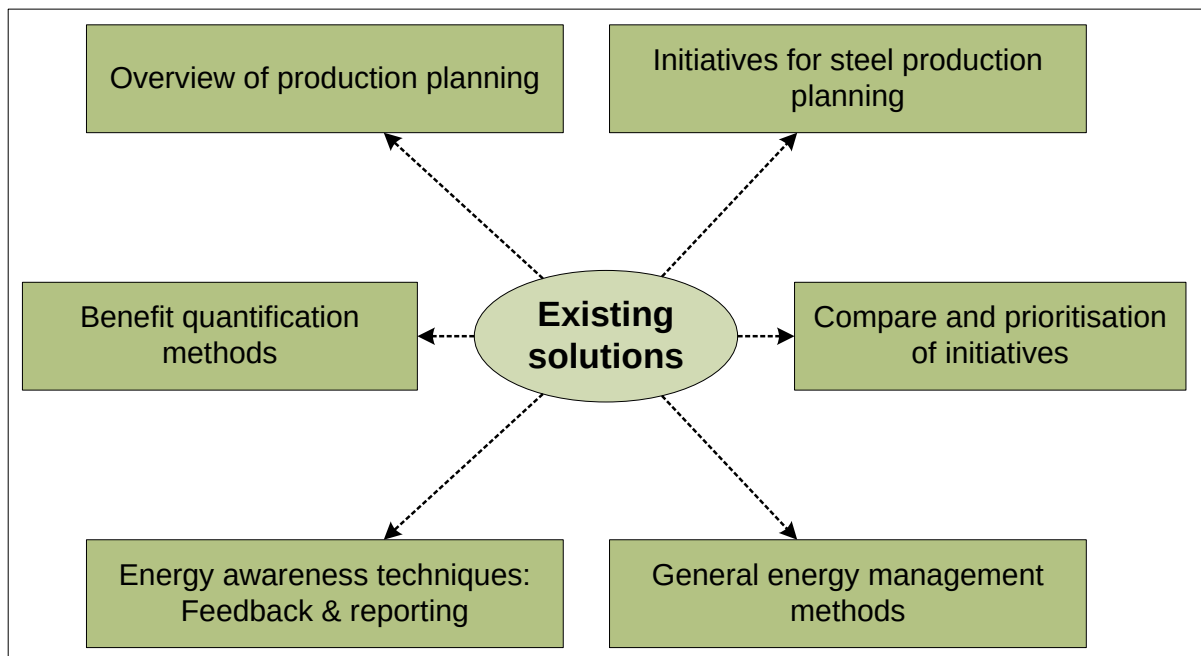


Figure 5: Summary of existing solutions discussed in the literature review

2.2. OVERVIEW OF PRODUCTION PLANNING

2.2.1. OVERVIEW

This section provides information on the basic background required to understand steel production planning. Elements of this type of production planning are discussed, providing a better understanding of the functions and critical role thereof. This further indicates where there are opportunities to adapt methods, and how the opportunities can be used to achieve energy cost savings by implementing initiatives. The discussion includes a review of production planning in other industries that focus on energy cost efficiency. Table 6

summarises the studies that were reviewed for this discussion, along with the criteria that were used. The most relevant of these studies are discussed in more detail.

Table 6: Summary of the literature survey related to energy cost focused production planning

Author	Application in the steel industry	General discussion of process	Discussion of an initiative	Focused on energy cost efficiency	Application on a South African case study	Integration of initiatives	Integration of energy sources/carriers
Hamer [42]		✓	✓	✓	✓		
Lin <i>et al.</i> [23]	✓	✓					
Maneschiijn [44]		✓	✓	✓	✓		
Swanepoel <i>et al.</i> [46]		✓	✓	✓	✓		

2.2.2. STEEL PRODUCTION PLANNING

A study by Lin *et al.* [23] developed a solution to integrate production planning between continuous casting and rolling mills. The study will be discussed in more detail in Section 2.3.3. There are significant differences between the presented solution and the method developed in this thesis, but that there are valuable aspects that can be used from their study [23]. The first is the description of the general process used when conducting production planning, as presented in Figure 6 [23].

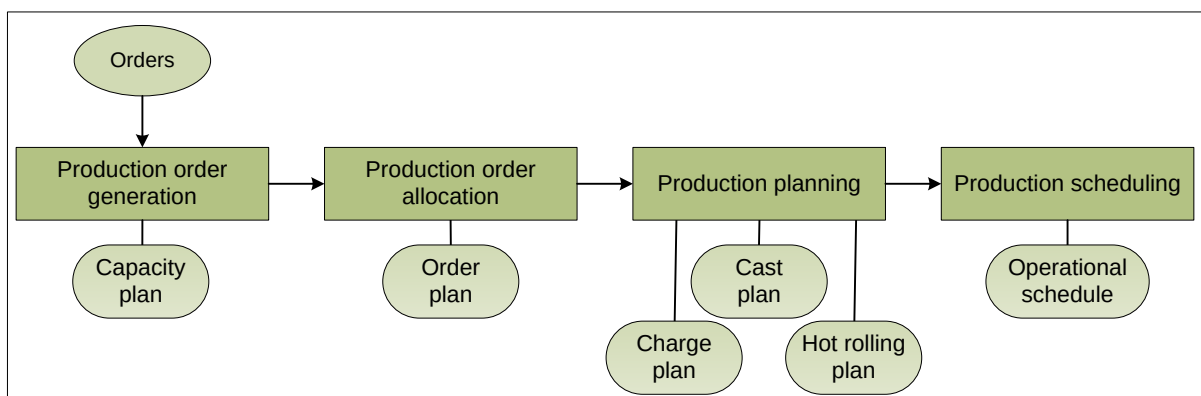


Figure 6: General process for production planning (as adapted from Lin *et al.* [23])

Figure 6 shows that several entities are involved with steel production planning; each of which has their specific outputs in the process [23]. The first step is receiving orders from the customer and determining whether there is sufficient capacity to produce these orders [23]. Such orders typically include the required date of completion, steel quality descriptions, the

quantity of the required steel, and the dimensions/profiles required [23]. The orders are prioritised and allocated to an order plan, which includes the latest orders as an input for production planning [23].

The production planning department is responsible for providing charge, casting and rolling plans (priority lists) to the production schedulers of different sections on the facility [23]. The production schedulers on these sections generate an operational schedule for their specific plants based on the requirements of production planning [23]. Figure 6 provides a general representation of how the process works. This serves as a valuable guideline when initiating investigations into a facility's production planning functions. This structure/process has to be determined for the specific facility upon starting with the investigations. Three reasons for the complexity of production planning in the steel industry are listed by Lin *et al.* [23] as:

- A large variety of decision variables need to be considered;
- Production planning has multiple objectives; and
- There are several interval-related uncertainties (interactive effects).

Due to these complexities, it is recommended that multi-objective optimisation methods be used when performing production planning on these facilities [23]. This implies that more than one output has to be considered when performing the integrated production planning while developing the solution [23]. This was done by Lin *et al.* [23] who introduced the concept of order sets. An order set is created by grouping planned casts together based on their similarities (such as nominal steel quality and nominal dimensions/profile requirements). This simplifies the production planning process by reducing the complexity and variety of orders that have to be scheduled [23].

By considering casts as an order set, it is possible to reduce setup changes between casts due to the grouping of similarities [23]. This concept can be valuable in the application of the methodology developed by this thesis. The resulting output of applying this methodology to a case study plant was an increased throughput at the continuous caster (concast), an increased hot charging rate, increased throughput at the rolling mill, and improved tundish utilisation [23]. Lin *et al.* [23], however, did not focus on adapting and integrating production planning initiatives, but rather on improving production planning processes in general.

2.2.3. RELEVANT PRODUCTION PLANNING IN OTHER INDUSTRIES

Swanepoel *et al.* [46]

In terms of production planning approaches that focus on reducing energy costs, a simulation model developed by Swanepoel *et al.* [46] for the cement industry should be considered. This

simulation model was implemented to reduce the peak time electrical energy consumption of cement mills [46]. One of the main problems that Swanepoel *et al.* [46] faced was the effect that switching off a mill for several hours would have on cement production. A simulation model was developed to predict the cement silo levels at different time periods in advance to determine the effect that the electrical load shifting would have on product availability [46].

In order to make such a prediction, it was necessary to first understand the production planning process of the facility and to consider the inputs that typically contribute to decision-making [46]. These inputs included factors such as planned maintenance, current availability of cement, production rates of equipment, and the predicted daily sales [46]. By using such a simulation model, Swanepoel *et al.* [46] was able to prove the feasibility of energy cost reduction by means of electrical load shifting on a cement plant without affecting production outputs negatively.

Maneschijn [44]

The simulation model developed by Swanepoel *et al.* [46] was later used by Maneschijn [44] to implement electrical load shifting on a cement plant. The application was on a South African case study, which was subject to similar conditions as the problem addressed by this thesis (but in a different industry) [44]. A fully automated approach could resultantly not be used to perform load shifting, and Maneschijn [44] used an awareness-based approach for the implementation strategy. This approach indicated to control room personnel when it was possible to switch off equipment during peak times by providing them with the required information and a suggested load shifting schedule [44].

Important aspects can be taken from both these studies and be adapted for use in the solution to the problem addressed by this thesis. The use of simulation techniques and prediction models by Swanepoel *et al.* [46] will be valuable when proposing changes to current production planning methods. Additionally, the use of an awareness-based approach by Maneschijn [44] can be used to address the unique conditions of a South African case study. The concerns of personnel can similarly be addressed by indicating how risks will be influenced by certain actions, thereby motivating the use of the suggested changes.

Hamer [42]

Another relevant study was in the precious metals industry. Following a study by Jordaan [61] on demand-side management in this industry, Hamer [42] analysed electricity cost saving opportunities on gold processing plants in South Africa. Jordaan [61] suggested load shifting in processing plants by completely switching mills off to a stationary position. This was found not to be feasible, but the issues were later resolved by Matthews and Craig [62] who

suggested that the rotational speed of the mill be controlled to reduce peak time consumption, rather than to eliminate it. This concept can also be of value in the BF-BOF process of steel-making by rather reducing energy intensity in peak times than stopping production completely.

Based on these studies, Hamer [42] proceeded with developing and implementing electrical load shifting on a gold processing plant. The study used production planning to simulate the effect of load management on the facility [42]. This study supports the use of production planning methods to reduce electrical demand during peak times – even in processes where equipment cannot be switched off completely as required [42]. Elements of this study are considered to be of value for the methodology developed in this thesis. The relevancy of the identified initiatives was evaluated by Hamer [42] based on the following criteria:

- The potential cost benefit of the initiative;
- The capital requirements to implement the initiative;
- The ease of implementing the initiative;
- The operational feasibility by using the existing systems; and
- The possibility of maintaining production and quality requirements.

This criteria is of value in similar applications, and can be considered in the development of the methodology in this thesis. Another criterion that Hamer [42] used was considering whether electrical load could be scheduled within the operational boundaries. The elements to be considered are listed below [42]:

- Production forecasts;
- Maintenance schedules;
- Reliability of equipment;
- Operational capacity of equipment;
- Energy intensity of equipment; and
- Available storage/buffers and its capacity.

It is seen that production planning has been used in other industries to reduce energy costs successfully. Thus, production planning is a feasible solution. These applications show that buffers in a process are valuable when implementing electrical load shifting initiatives, but that there are ways to manage production without them. Some components of the studies in other industries are also of value to this thesis. However, these studies typically do not focus on energy sources other than electrical energy, and they do not integrate multiple initiatives. The value of production planning in energy cost reduction is seen from these studies.

2.3. EXISTING PRODUCTION PLANNING APPROACHES

2.3.1. OVERVIEW

This section provides a more detailed discussion of some of the applicable research evaluated in Section 1.3.2. All the studies were evaluated at the hand of the provided criteria, and shortcomings of the research were discussed in Section 1.3.2. The most relevant research for each evaluated field of study is presented in this section.

2.3.2. GENERAL STEEL PRODUCTION ENERGY MANAGEMENT

Overview

An evaluation of existing research of general steel production energy management was provided in Table 1 (Section 1.3.2). The most relevant studies are discussed below.

He and Wang [14]

He and Wang [14] conducted a study to list energy efficiency technologies and practices applicable to the steel industry. This includes case studies from around the world, and details of the energy and cost savings of the relevant initiatives. The study highlights that new plants tend to be more efficient than old plants. It indicates that using the best available technology on the steel industry could improve the energy efficiency by 20%. The literature review conducted by He and Wang [14] includes a list of 158 iron and steel energy efficiency measures and technologies.

As the focus of this thesis is on production planning initiatives at a steelmaking facility using the BF-BOF technique, the initiatives evaluated by He and Wang [14] were filtered accordingly. One of the relevant initiatives evaluated by He and Wang [14] is improved process monitoring and control, as discussed by Worrel *et al.* [28]. This discussion is part of a programme referred to as ENERGY STAR®, which assists steel manufacturers in the United States (US) with energy efficiency. This report contains a variety of energy efficiency initiatives relevant to the iron and steel industry, but mainly with application in the US.

He and Wang [14] also highlighted hot charging as a potential initiative to be implemented on a steelmaking facility, and referenced an application thereof in Japan.⁸ The study indicates that this technology was first used in Japanese steel companies, and that hot charging rates

⁸ National Energy Conservation Centre, "Continuous casting billet hot charging technology," National Energy Conservation Centre, 2013. [Online]. Available: http://jnjs.0co2.com.cn/jnzx_web/technology/1248/details.html. [Accessed 30 April 2018]

of between 65% and 80% are reached at these facilities. The detailed discussion of this study also mainly focuses on technological and infrastructural requirements relevant to hot charging.

Worrel *et al.* [28]

The report compiled by Worrel *et al.* [28] provides a guide for energy and plant managers on how to improve energy efficiency on different types of plant in the steelmaking industry. The guide intends to reduce energy consumption and environmentally hazardous emissions using cost-effective approaches without neglecting the quality of products. Several of the solutions focus on technological improvements (which are not applicable to this thesis). Some of the solutions, however, do focus on energy efficiency measures that can be followed. The report emphasises the importance of energy management and provides a framework for use in the steelmaking industry.

Worrel *et al.* [28] also highlights the potential of a hot charging initiative, which is relevant to this thesis. No specific guideline is provided to increase hot charging, but it is indicated that hot charging could result in production increases of up to 6%. Additionally, it is mentioned that energy reductions of 0.6 GJ/t to 0.7 GJ/t steel were reached in previous case studies through hot charging. General infrastructural guidelines for hot charging are provided – all of which would require capital investments, which are not relevant to this thesis. The concept of an energy management framework to establish energy cost savings, however, provides valuable information.

Breytenbach [24]

In terms of energy efficiency initiatives in the South African steel industry, Breytenbach [24] developed an operational framework for electricity cost reduction. This framework provides a step-by-step approach, which is based on the *plan-do-check-act* (PDCA) cycle described by ISO 50001, that is specifically relevant to steelmaking facilities. Breytenbach focuses on operational changes, but only identifies projects with electrical energy cost saving opportunities. An energy management strategy is used to identify potential initiatives on steelmaking facilities, which is an important aspect to be used as part of this study. Such an approach requires commitment from management, and uses several techniques, including important energy awareness aspects.

National Cleaner Production Centre of South Africa [25]

As part of the previous work on South African plants that Breytenbach [24] reviewed, a world-class manufacturing programme at a South African steelmaking facility was referenced. This programme was initiated by the National Cleaner Production Centre of South Africa [25] and

entailed using an energy management system to optimise energy consumption at the facility. This was also done in alignment with ISO 50001, and entailed various steps for identifying and utilising opportunities by targeting significant energy users at the facility. Twelve projects were implemented with minimal capital investment.

The report only discusses one project relevant to this thesis, namely, load shifting [25]. This entails reducing the electrical energy consumption during peak electricity times and rather consuming electricity during off-peak hours. The report does not give any specific details on which plant sections load shifting was implemented on, or what procedures were followed to establish load shifting [25]. The use of such an initiative on a steelmaking facility is, however, of value for the development of the methodology.

Remus *et al.* [26]

Remus *et al.* [26] summarises the best available techniques for steelmaking facilities as provided by the European Commission. Breytenbach [24] also assesses these techniques. Remus *et al.* [26] highlight important factors for energy efficiency in steelmaking facilities. The following factors from this study are considered during the development of the methodology:

- Optimising energy consumption;
- Monitoring energy flow;
- Reporting and analysis;
- Evaluating energy consumption with historical performance; and
- Continuously identifying energy opportunities.

Dondofema *et al.* [8]

Dondofema *et al.* [8] researched the evolution of the South African steelmaking industry from an industrial engineering perspective. This included focusing on the history of the industry in South Africa, and doing a literature review of published research relevant to the field. The published work that was evaluated focuses on industrial engineering, and includes operational and production management initiatives. Dondofema *et al.* [8] found that there are limited publications for production planning applications in the South African steelmaking industry. The research found during this survey is the following:

- The investigation of reducing the holding of consumable items [63];
- The organisation of maintenance on hot rolling mills [64];
- The investigation of the impact of poor quality management system utilisation [65];
- The applications on EAFs [66]; and
- The exploration of the need for planned maintenance [67].

These initiatives do not focus on the same areas or approaches discussed in this thesis. This lack in research highlights the need for an integrated production planning approach in South Africa that focus on energy cost efficiency.

2.3.3. STEEL PRODUCTION PLANNING METHODS

Overview

Existing research relevant to steel production planning methods was evaluated in Table 2 (Section 1.3.2). The most relevant studies are discussed below.

Karwat [32]

Karwat [32] uses a mathematical approach to optimise production based on available equipment. The model focuses on the time that a batch of steel spends at each specific station, and optimises the schedule to ensure that the minimum time is used to process the steel. The research done by Karwat [32] is specific to a plant where equipment works efficiently. There did not seem to be any resistance to the implementation of an automated solution.

The application for the study done by Karwat [32] focuses on a plant using the BF-BOF method, and includes the production scheduling up to the rolling mill, which highlights the benefits of hot charging steel. The main outcome of the model is maximum production and it thus does not consider energy cost efficiency. It is assumed that there are sufficient steel orders for the plant to produce the maximum amount of steel possible. This is not the case for a South African steel plant in the current conditions, as discussed in Section 1.2.2. Therefore, the strategy will not be beneficial to South African steel producers.

Merkert *et al.* [21]

Merkert *et al.* [21] investigated the importance of production scheduling when considering energy consumption in industrial applications. The study highlights several challenges and opportunities relevant to various industries, including steel manufacturing. The study focuses on production planning as an *enabler* for energy consumption improvements, and mainly highlights the use of modelling and algorithms as methods for improving production planning. Some of the most relevant techniques evaluated by the study are:

- The use of real-time scheduling to evaluate the immediate effect of a possible action;
- The use of different demand-side management techniques (peak clipping, energy efficiency and load shifting); and
- The use of an energy management system (such as ISO 50001).

The study also indicates that buffers increase the capacity to consider energy as part of production scheduling due to the operational flexibility that it provides. Production scheduling with the aim of improving energy efficiency was evaluated in various industries, such as iron and steel production plants, and cement manufacturing plants.

Xu *et al.* [38]

One of the applications on a steelmaking facility is to increase hot charging, as researched by Xu *et al.* [38]. The study identifies the loss of energy due to cooling steel as an opportunity to reduce energy by improving production planning. The application was, however, on a melt shop and not on a BF-BOF application; however, it does imply that buffers could be induced in the production process. The approach was to generate the melt shop schedule and the hot rolling schedule separately, but basing the one on the result of the other. In the application of this thesis, this approach will have to be adapted as the BF-BOF schedule cannot be adapted based on the rolling mill schedule. The process therefore needs to be evaluated in an integrated manner.

Dao-fei *et al.* [34]

Dao-fei *et al.* [34] evaluated the production planning methods used on a steel plant. The case study plant had five BOFs, four ladle furnaces, and four concasts, and is significantly larger than a typical South African steelmaking facility [34]. The production process is described by this study as a *static structure network*, and it is highlighted that manual production planning methods do not dynamically adapt to operational changes in the procedure [34]. Uncertainties regarding operation and transportation times are also not considered in the process [34].

The optimisation model is compared with actual data using a simulation and is not implemented practically [34]. According to the evaluation, an optimisation model is required to handle these uncertainties and to adapt according to the latest information [34]. The focus of this model is on production efficiency and time optimisation, thus neglecting the energy efficiency possibilities of production planning [34]. The production planning solution considers various aspects. The following aspects have to be considered when conducting production planning [34]:

- Average use of equipment;
- Average waiting time for each charge;
- Average length of a queue; and
- The time difference between tapping and pouring.

Lin *et al.* [23]

The study by Lin *et al.* [23] developed a solution to improve the integrated production planning between the concast and the milling sections of a steelmaking facility. The relationship between the casters and the mills is described as *complex* and having *sophisticated constraints*, which often causes a bottleneck in steel production [23]. The lack of coordination between these processes is identified as a *gap which needs to be filled* based on existing studies focused on production planning [23]. It is, however, highlighted that limited studies focus on the integrated production planning between these sections [23]. The integrated studies that were considered include the following [23]:

- An overview of production planning problems, and a review of production planning methods and systems used when considering these sections as an integrated entity, as conducted by Tang *et al.* [68].
- A single-objective model integrating production planning and orders, as conducted by Aouam and Brahimi [69].
- The modelling of the integrated sections by using heuristic techniques and mathematical modelling in a hybrid network, conducted by Cowling and Rezig [70].
- An intelligent integrated planning system to increase hot charging at a Chinese steel manufacturer, as conducted by Lv *et al.* [71].
- Software development techniques used to solve the production planning complexity, as developed by Tu *et al.* [72].
- A batch-planning model taking several objectives into account, as developed and improved by Zhu *et al.* in two separate studies [73, 74].
- Previous research conducted by Lin *et al.* [75] using a modelling framework based on production orders, and conducting research-driven predictions to solve the integrated production planning problem.

Lin *et al.* [23] identified the shortcomings of these studies to be the focus on single-objective solutions, or the transformation of multi-objective models into single-objective solutions. These shortcomings were addressed by Lin *et al.* [23] by developing a multi-objective solution for integrated production planning between the concast and milling operations. Some valuable elements from this approach can be used to develop the solution in this thesis. These elements were discussed in more detail in Section 2.2.2 of the literature study.

The shortcoming of the research conducted by Lin *et al.* [23] regarding this thesis is that the developed model focuses on improved production planning by introducing order sets, which consider several casts as one operational input. This will not be possible for a steel production

facility in South Africa as the plants are significantly smaller and there are not sufficient orders to consider casts in this way [5].⁹ The plant for which Lin *et al.* [23] developed the solution was listed 274th in the Fortune Top 500 iron and steel companies in the world in 2015. The conditions on this plant are therefore significantly different than those at a South African steelmaking facility.

The solution developed by Lin *et al.* [23] also focuses on the improved integration of the steelmaking schedule, but does not focus specifically on adapting and integrating energy cost saving initiatives on these sections. Resultantly, there is also not any focus on benefit quantification methods, or dynamic prioritisation of initiatives [23]. The study is considered to support the identification of the gap in the integration of the sections in steelmaking facilities, but suggests a different approach to solving the problem than the one developed by this thesis.

2.3.4. PRODUCTION PLANNING FOR ENERGY COST REDUCTION

Overview

The existing research relevant to production planning for energy cost reduction was evaluated using Table 3 (Section 1.3.2) and the provided criteria. The most relevant of these studies are discussed below.

Gahm *et al.* [39]

The first study under consideration is a literature survey conducted by Gahm *et al.* [39] that evaluated the value of energy efficient scheduling in manufacturing companies. The survey was done by identifying journal articles that comply with several criteria and keywords, and determining the effect that these studies had on energy efficiency by using production scheduling. The research highlights the importance of energy efficiency as part of sustainable development. From the research it was concluded that production scheduling offers potential for incorporating energy efficiency in practical applications, and that production scheduling is a preferred method of achieving energy cost savings due to the low investment cost associated with it.

Rager *et al.* [18]

The importance of energy efficiency for manufacturing is further emphasised by Rager *et al.* [18] for managing rising energy costs as well as the increasing public perception of environmentally conscious operations. This research specifically considers energy

⁹ R. Wilkinson, "Import prices on steel not the best solution," *Creamer Media's Engineering News*, 1 July 2016.

consumption as part of short-term production planning (referred to as an organisational measure). Rager *et al.* [18] mentions that organisational measures are preferred over technological measures due to the lower cost required for implementation. The study focuses mainly on reducing losses between the conversions from applied energy sources to final energy sources by managing and stabilising the consumption profile during production.

The first critical aspect from this research that is used during this thesis is to consider energy consumption when performing production planning and scheduling. Secondly, the concept of managing end production to minimise losses during energy conversions also plays an important role in the development of the solution. The study by Rager *et al.* [18] used decision-making algorithms to determine the desired production plan, which is a concept that is incorporated into this thesis.

Swanepoel *et al.* [46]

Research on the optimisation of energy cost by means of production planning was conducted by Swanepoel *et al.* [46] (as briefly discussed in Section 2.2.3). This research was specifically aimed at implementations on the cement industry, and was practically implemented on four South African plants. The concept of the study focused on identifying the relevant constraints for production outputs, and managing the constraints according to dynamic energy costs in a single operational modelling system. The implementation resulted in an energy cost saving of 7.1%, which validates the effect that production scheduling can have when the purpose is energy cost efficiency.

Swanepoel *et al.* [46] used energy awareness related techniques to achieve the desired result. The constraints were used to determine whether production targets would be met, and a suggestion for a production plan was provided. This was done using the PDCA approach of ISO 50001. Although several aspects of the study conducted by Swanepoel *et al.* [46] can be used for the methodology developed in this thesis, there are a few critical differences: the main difference being the application on a steelmaking facility. Cement production can be delayed with buffers, and equipment can be switched on and off as required. However, as previously discussed, this is not the case for BF-BOF steelmaking facilities.

2.3.5. PRODUCTION PLANNING FOR PRODUCTION COST REDUCTION

Overview

Production planning for production cost reduction was evaluated in terms of existing research using the relevant criteria in Table 4 (Section 1.3.2). The most relevant studies are discussed in more detail below.

Lochmüller and Schembecker [50]

A study by Lochmüller and Schembecker [50] not only considered the optimisation of production scheduling, but also included operating conditions and the equipment dimensions that need to be considered during plant design. The purpose of the study was to minimise both operating and capital costs on a batch production plant with practical applications on the production of pharmaceutical products. Lochmüller and Schembecker [50] highlight that the initial solution is critical for production planning, and that the original design of a facility is relevant to the practicality of planning production efficiently. This study investigates the trade-off between organisational and technological solutions.

Even though the research by Lochmüller and Schembecker [50] focuses on a completely different industry than this thesis, it highlights the importance of production planning by using the available technology and plant setup. The strategy focuses on the effective use of available equipment for production needs. It also highlights that buffers in the process have to be used effectively to ensure optimal production. These concepts are incorporated as part of the development of the solution for this thesis. The study was, however, done on a plant where equipment dimension changes were adaptable, and not on an existing plant where old equipment must be used. The process under discussion is also a batch process, unlike the BF-BOF steelmaking process.

Biondi *et al.* [48]

Research by Biondi *et al.* [48] focuses on improving the coordination between production planning and maintenance scheduling. It highlights the importance of planning and scheduling on processing plants. Biondi *et al.* [48] focuses on improving equipment lifetime and production efficiency by scheduling maintenance and production more effectively. Although the study does not consider energy cost efficiency, it does use aspects of an awareness-based approach to establish improved performance. An example of the developed model is applied to the steelmaking industry, but focuses on the EAF production method and not the BF-BOF production method.

Moshidi [52]

Moshidi [52] conducted a study of effective maintenance planning at a South African steel manufacturer. The study was done from a business administration point of view, and focused on the responsibilities of maintenance planners (with relevance to operational planners in general) [52]. The literature review of this study included an investigation of the responsibilities of planners in a steelmaking facility [52]. This was compared with the actual work that has to be done by these planners at the specific South African steel manufacturer that was

considered [52]. The output of the study by Moshidi [52] recommended how maintenance planning could be improved at the plant (and thus also other plants with similar conditions) [52].

The purpose of the improved maintenance planning investigated by Moshidi [52] is to rather be proactive than reactive when doing maintenance. This is to ensure that production capacity is available when needed, which leads to reduced overall maintenance costs [52]. The issues at the steel manufacturer were highlighted as not having standardised planning methodologies and neglecting the application of specified principles [52]. Another problem was that the plant under discussion was old and had outdated equipment [52]. Due to the age of the plant, there were also several generations of employees that had been in planning positions, and tasks becoming unclear over the years [52]. This resulted in resistance to change.

The research shows that planners have a high workload. Solutions for improved production planning should focus on relieving the workload rather than adding to it [52]. According to Moshidi [52], some personnel are lower skilled; therefore, solutions should consider the skill level. Another important aspect of implementing initiatives is providing feedback to personnel and ensuring that the benefits are realised as soon as possible [52]. This encourages personnel to cooperate and maximise the results of initiatives. Other important guidelines provided by Moshidi [52] are:

- To use available technology;
- To focus on time efficiency;
- To assess the available finances for improved process; and
- To strictly follow the processes of the implementation.

2.3.6. INTEGRATION OF SOLUTIONS

Overview

The integration of solutions were evaluated from existing research in Table 5 (Section 1.3.2) by using the listed criteria. The most relevant of this research is discussed in more detail in this sub-section.

Marais [58]

Marais [58] focused on integrating existing solutions for mine compressed air systems. The study evaluated existing solutions for reducing mine compressed air energy costs and integrated them into a single approach [58]. The study evaluated the potential energy cost benefit of different existing solutions on a facility and determined which of the initiatives would be beneficial to apply practically to the facility [58]. Specific focus was placed on accurately

determining the realistic potential benefit of an initiative before prioritising it, and monitoring the performance afterwards [58]. Several of these concepts can be used during the development of the solution in this thesis.

David *et al.* [54]

David *et al.* [54] applied an integrated optimisation model aimed at assisting steelmakers with strategic decision-making to steelmaking facilities. This approach focused on integrating all the sections on a steelmaking facility and considered various factors to reduce the cost of production [54]. Factors included the cost and quality of raw materials, the downstream effect thereof, and optimising the liquid iron distribution between different sections [54]. Although a part of the model included production planning, it mostly focused on optimising end production and ensuring that the most beneficial products are produced [54]. This included considering factors such as the most profitable and demanded products [54].

Gajic *et al.* [56]

Gajic *et al.* [56] implemented an optimisation system that integrated production and electricity cost on a stainless steel melt shop. The system mainly focused on the integration between achieving production outputs and managing electricity consumption of the melt shop around time-of-use (TOU) tariffs to reduce costs [56]. At the same time, the integration also attempted to achieve an increased hot charging rate of the primary rolling mill [56]. This was achieved by using mixed-integer linear programming and calculating an automated solution for the most cost-effective production plan [56]. The melt shop uses the EAF production method, and it is thus possible to pause and resume production as needed [56]. The focus was on managing the electricity consumption of the EAFs and ladle furnaces of the facility [56].

2.4. INITIATIVES FOR STEEL PRODUCTION PLANNING

2.4.1. OVERVIEW

The purpose of this section is to identify and briefly review existing initiatives in steel production planning for use in the development and application of the methodology. Several factors were considered during the review of possible initiatives to keep the discussion relevant to the study. Some factors considered during the review of existing literature include:

- Little to no capital should be required;
- The solution should not focus mainly on technology (possibility of an ISO 50001-based implementation strategy);
- Improvements should be achievable by focusing on production planning; and

- The initiative should have energy cost benefits without affecting production negatively.

All of the production planning initiatives reviewed in this section were developed and / or implemented on facilities where no other production planning initiatives were implemented. There is therefore no effect that one initiative could have on another that needs to be considered during the evaluation of these initiatives in this chapter. In the integrated cost model developed by this study, the sensitivity of each initiative will be considered.

2.4.2. HOT CHARGING OF THE PRIMARY ROLLING MILL FURNACE

Tu *et al.* [53] evaluated existing literature for production planning in hot rolling planning, and found that previous studies considered the product quality, productivity and delivery requirements of steel. According Tu *et al.* [53], it is necessary for such production planning systems to also consider the requirements of downstream production lines. The aim of the study is to increase the production of primary hot rolling plants by considering all these factors. The study uses complex mathematical modelling and algorithms, and considers various practical constraints. Although the solution developed by the study was not implemented practically, the study used computational results to show the potential effectiveness of the method [53].

A report on global warming countermeasures summarises the energy saving technologies used in Japan and briefly discusses the concept of hot charging versus direct loading [36]. Hot charging is described by this report as the reheating of casted steel while it still contains some heat, while direct loading completely bypasses the reheating furnace [36]. According to the report, almost all Japanese steelmakers have a hot charging rate of 100%, but there are only a few cases where direct loading takes place [36]. The benefit of hot charging was reported to be an almost 20% reduction in fuel consumption by the furnace [36].

The input cost of implementing such a project will be dependent on the infrastructure that is already available [36]. If no equipment is in place to hot charge steel from the concast to the mill furnace (such as the required cranes and conveyer system), then the payback period can be up to 11 years [36]. However, if all equipment is already in place there will be no payback period. The report does not focus specifically on the type of equipment required, or what changes need to be made by production planning to realise these benefits [36].

A study that focused on increasing hot charging at a steel mill in south-east Turkey used a software developed by PSImetals Planning, which increased the hot charging ratio from 5% to 54% over a five-year period [37]. This increase in hot charging reportedly resulted in a 22% reduction in furnace gas consumption [37]. The focus of the PSImetals Planning software was to decrease energy consumption in the reheating furnace by lowering stock levels and to

decrease slab movements to reduce lead times [37]. The basic concept was to identify hot charging opportunities by synchronising casting and rolling schedules [37].

The software developed by PSImetals Planning [37] used a push-pull approach: the orders (push) are used to determine which steel should be casted (pull). A vital aspect to the success of this study was to reduce the amount of cold stock and to better synchronise the casting schedule with the rolling schedule. The software used orders placed four weeks in advance to identify opportunities, which were used to generate the short-term production schedules (three days) [37]. Although the description of the initiative mentions several factors that need to be considered when improving hot charging, it does not focus on the details of developing and implementing the solution.

Chakravarty *et al.* [33] identified and implemented several methods to improve the operating practices of a reheating furnace in a hot strip mill. One of these initiatives included increasing the percentage steel that is hot charged in the furnace. An evaluation of the benefits of hot charging was done by analysing data using regression models. The most relative regression models were the comparison between production and fuel consumption (GJ/t), and the comparison between hot charging percentage and fuel consumption (GJ/t) [33]. These models can be used to evaluate the effect of hot charging on furnace fuel consumption.

For the implementation, the effect of hot charging was reducing the 27 minutes spent in the furnace [33]. The main factor restricting hot charging was poor coordination between the casting schedule and the furnace rolling schedule [33]. The schedules were compiled separately, which led to differences in the sequences scheduled at the two sections [33]. By analysing the data, it was found that it was theoretically possible to hot charge 79.6% of the steel while only 61% was being hot charged in practice [33]. The cause for this difference was analysed, and was allocated to the following reasons [33]:

- Weekly furnace shutdowns;
- Scheduling constraints;
- Slab diversion;
- Furnace breakdowns;
- Caster breakdowns;
- Constraints with using the cranes; and
- Start-up time of the furnace.

Measures taken to improve the percentage hot charging included: upgrading the control equipment at the caster (presumably to improve communication with the furnace); and prioritising any casted slab after completing the furnace rolling schedule [33]. The study does

not provide details on how these measures were used to improve the percentage hot charging. It is, however, noted that hot charging improved to 68%, which led to an energy reduction of 6.61% [33]. Even though this study does not provide sufficient detail to implement such an initiative, it does provide guidance for data analysis and benefit quantification of a hot charging initiative.

2.4.3. LADLE FURNACE LOAD SHIFTING

The concept of electrical load shifting by utilising varying electricity prices is a known technique for reducing energy costs without affecting production outputs [21]. This is typically done by using available buffers in a process to move electrical energy intensive processes to less expensive time periods. A study by Merkert *et al.* [21] discusses the correlation between energy and scheduling, and highlights the value of electrical load shifting. The study briefly discusses the possibility of using the energy intensiveness of different batches in a batch process to shift electrical load rather than inducing buffers in the process [21]. This could provide new opportunities for energy cost reduction in a process such as steel production.

The concept of electrical load shifting was also considered by Hadera *et al.* [41] for a melt shop section of a stainless steel plant. Hadera *et al.* [41] suggest increasing energy awareness on a production planning level, and resultantly using it as an additional input for production scheduling [41]. The high electrical energy intensity of the EAF and ladle furnaces used in this process provided an opportunity to move electrical energy consumption to less expensive time periods [41]. Using an EAF provided the opportunity to induce production delays, and resultantly manipulate production times around electricity tariffs [41]. Inducing such production delays will be more complex in other steel production processes due to the continuous production process.

A similar study by Yuan-yaun *et al.* [47] managed the electrical energy consumption of EAFs and ladle furnaces around varying electricity tariffs. This was done by determining the start and end times of casting sequences and attempting to schedule delays between sequences during more expensive time periods [47]. Mathematical modelling was used to determine an optimal production schedule, which was validated by computational results [47]. The study, however, does not provide information on the practical implementation of the approach, and how it was integrated with the existing approach of plant personnel.

2.4.4. LADLE AND CRANE TIME LOSS REDUCTION

A study by Liu *et al.* [49] developed a software to assist with reducing ladle and crane time losses to reduce energy losses. The concept of using this software is to reduce time losses between the concast and its preceding processes by improved planning of which crane and

ladle to use for production [49]. The software was developed after investigating and understanding the decision-making process at the facility, and used mathematical models to provide suggested schedules from the required inputs [49]. Although the software was not used practically, it was run on actual data. The study, however, does not provide sufficient results to determine the possible benefit of such a solution.

2.4.5. PRIMARY ROLLING MILL APPORTIONMENT MODEL

A study by Lu *et al.* [43] evaluated the possibility of arranging billets with similar specifications and thermal performance together in a furnace to improve heating quality and provide energy savings. The specifications used to group billets were the width of billets, the production rhythm, and the steel quality [43]. This study found that these aspects contribute to the energy consumption to reheat a bloom in a furnace. The results of the case study indicated that considering these aspects when performing production planning could lead to reduced energy consumption in the furnace [43].

Lu *et al.* [43] used various heat transfer and quantification methods to evaluate the effect of different factors on the energy consumption of a furnace. It was concluded that improved maintenance procedures are required to reduce the time that a billet spends inside a furnace (faster reheating rhythm) [43]. To utilise the benefits of the lower energy consumption for smaller width billets and certain steel qualities, production planning has to arrange these blooms better [43]. It is important to note that these factors influence furnace energy consumption and can be used when implementing production planning initiatives.

2.4.6. PRIMARY ROLLING MILL LOAD SHIFTING

Several electrical energy cost reducing initiatives were evaluated by Breytenbach [24] during the development and implementation of an energy management framework. Several initiatives focused on demand-side management by means of electrical load shifting [24]. One application of this strategy is to use the slab yard or torpedoes as a buffer for reducing the peak time electricity consumption of the rolling mills [24, 76]. Hot rolling was identified as the second-largest consumer of electrical energy; therefore, reducing peak time consumption could have significant cost benefits [76].

Ashok [77] also proved that it is possible to achieve energy cost benefits on a rolling mill by implementing a load shifting initiative. This study achieved a 5.2% electricity cost saving by rescheduling production, thus proving that it is possible to reduce costs on a rolling mill by means of optimal process scheduling [77]. During this study, the steel profiles and maintenance schedules were evaluated, and scheduling was adapted according to the most beneficial conditions in terms of TOU tariffs [77]. The algorithm used to optimise production

schedules also considered various constraints in the process, thus ensuring that production requirements are still achieved [77]. This initiative can be incorporated as part of the integrated cost model for steel production planning.

2.5. IMPLEMENTATION, INTEGRATION AND ASSESSMENT TECHNIQUES

2.5.1. OVERVIEW

This section discusses the different *tools*, which focus on production planning, that can be used for energy management. All the tools might not be directly relevant to the thesis, but will be adapted in the development of the methodology, and be used when implementing the methodology on a case study plant. The focus is on solutions that require little to no capital and that focus on operations. The evaluation is kept concise, and only the most relevant studies for use in the development of the methodology are discussed in detail.

2.5.2. COMPARE AND PRIORITISATION OF INITIATIVES

Summary

Different approaches are used to compare and prioritise the implementation of identified initiatives on the same facility. The approaches often consists of various methods to determine the most beneficial conditions for the specific facility. Table 7 summarises a few studies that were reviewed for the discussion of such approaches along with the criteria used. The most relevant research is discussed in more detail.

Table 7: Summary of the literature survey regarding the identification and prioritisation of initiatives

Author	Application in the steel industry	Methods for comparison	Methods for prioritisation	Relevant to energy and production	Solution can be adapted for another facility	Integration of energy sources	Application on a South African case study
Breytenbach [24]	✓	✓	✓		✓		✓
Stoddard [78]		✓	✓		✓		

Breytenbach [24]

Breytenbach [24] developed a framework that can be used to identify, compare, prioritise and implement electricity cost reduction initiatives in the South African iron and steel industry. The study focused specifically on opportunities that require no capital expenditure by using an

ISO 50001-based energy management system [24]. This framework was developed to form part of a larger energy management strategy; some aspects can be included as a useful tool in the methodology developed by this thesis [24]. Breytenbach [24] conducted an extensive literature review on existing comparison and prioritisation models to develop this relevant approach.

The prioritisation component of the framework developed by Breytenbach [24] was identified as a valuable component to include in the methodology. This will, however, have to be adapted as it does not focus specifically on production planning but rather only on electrical energy management opportunities. The basic concept of this prioritisation model is to allocate values to variables relevant to the identified initiatives, and to use the output of a calculation to rank the initiatives [24]. An adaption of the calculation used by Breytenbach [24] to prioritise initiatives is provided in Equation 1.

Equation 1: Initiative ranking calculation for prioritisation (adapted from Breytenbach [24])

$$\text{Initiative ranking} = [(x + y + z) + (A + B + C)] \times [P_{t,i} + P_{i,i}]$$

Table 8 provides the descriptions and allocated values of the variables in Equation 1. It is important to note that a negative value is allocated if capital is required by the plant, which results in a lower ranking for such an initiative [24].

Table 8: Description and allocated values of variables used by Breytenbach [24]

Variable	Description	Ranking
x	Energy efficiency initiative	3
y	Peak clipping initiative	2
z	Load shifting initiative	1
A	External funding	2
B	Section 12L funding	1
C	Plant capital required	-2
$P_{t,i}$	Total power usage ranking	High to low based on power raking
$P_{i,i}$	Energy intensity ranking	High to low based on intensity ranking

This approach developed by Breytenbach [24] will be adapted to be specifically applicable to steel production planning initiatives in the methodology. The method will also be adapted to account for different energy sources, and to consider production benefits of the identified initiatives. Some of the components discussed by Hamer [42] for use in the precious metals industry will be integrated with this model to provide an effective approach to address the research objectives of the thesis.

Stoddard [78]

Another approach that can be adapted and integrated with these methods to identify, evaluate and prioritise initiatives is the methodology developed by Stoddard [78] to achieve energy cost savings. Even though the aim of implementing this methodology is identifying opportunities for technological improvements, some of the concepts can be valuable for the application at hand [78]. The basic methodology followed by Stoddard is provided in the form of a list of steps [78]:

- Generate historical trends
 - Create a database from the available past data
- Assess the current use of energy
 - Obtain a list of plant equipment
 - Determine the power ratings for different equipment from historical data
 - Estimate energy use of equipment by using production data
 - Visually display the energy consumption and cost of different equipment
- Recommend energy efficiency opportunities
 - Use the findings from the previous steps to identify significant energy users
- Develop a plan to identify, evaluate, implement and review existing projects
 - Understand the process from discussions with plant personnel
 - Obtain data relevant to the projects
 - Map the current process and its progress/status
 - Develop a new map for the process

Even though the methodology developed and implemented in this thesis will not focus on technological improvements, historical data is useful for identifying opportunities. Some of the steps used by Stoddard [78] will be used as part of the development of the methodology.

2.5.3. GENERAL ENERGY MANAGEMENT METHODS

Summary

Various approaches exist for conducting energy management. The purpose is often to improve energy efficiency by means of operational improvements. Table 9 summarises the studies that were reviewed for this discussion, along with the criteria used.

Table 9: General energy management literature survey summary

Author	Focused on energy management	Practical application on a facility	Solution can be adapted for another facility	Integration of energy sources	Application on a South African case study	Provides guidelines for practical implementation
Breytenbach [24]	✓	✓	✓		✓	✓
D'Antonio, Bedolla and Chiabert [79]			✓			✓
ISO [80]	✓		✓			✓
Maneschijn [81]	✓	✓	✓		✓	✓
Moeuf <i>et al.</i> [82]			✓			✓
Pelser, Vosloo and Mathews [83]	✓	✓	✓		✓	✓
Schulze <i>et al.</i> [84]	✓		✓	✓		✓
Swanepoel <i>et al.</i> [46]	✓	✓	✓		✓	✓

D'Antonio, Bedolla and Chiabert [79] and Moeuf *et al.* [82]

A popular approach is using lean manufacturing [79, 82], which main focus is to reduce unnecessary wastages by optimising a manufacturing process. This consists of evaluating a production line critically, and determining which elements can be reduced or eliminated in order to improve productivity [79, 82]. Although the focus is not necessarily purely energy driven, the basic concept can be of value when performing production planning.

ISO [80]

A more energy orientated approach with similarities to lean manufacturing is using ISO 50001. "ISO 50001:2011 – Energy management systems" [80] is a voluntary standard developed by ISO. The main purpose of this standard is to provide a guideline that organisations can use to improve energy management [80]. Apart from improved energy performance, compliance with ISO 50001 has been reported to have several advantages for an organisation [85].

An ISO 50001-based approach towards energy management has proven to be beneficial in several industries as validated by a variety of studies in different industries [24, 86, 87, 88, 89, 90, 91, 92]. Even though the aim of the methodology developed in this thesis is not to achieve ISO compliance, it is still beneficial to understand the main components of an ISO 50001-based approach. Some of these elements can then be used in the development of a solution

and for the practical application of initiatives. ISO 50001 is based on the PDCA cycle, which focuses on the continuous improvement of the energy management of an organisation [85].

Pelser *et al.* [83]

A basic flow diagram of the ISO 50001 cycle is provided in Figure 7, as obtained from Pelser *et al.* [83]. The most important concept of this flow diagram is the use of a *continuous improvement* feedback loop [83, 85, 91]. This feedback loop ensures that methods are revised according to findings and achieved performance, which provides the opportunity for improving the approach after the initial implementation [83, 85, 91].

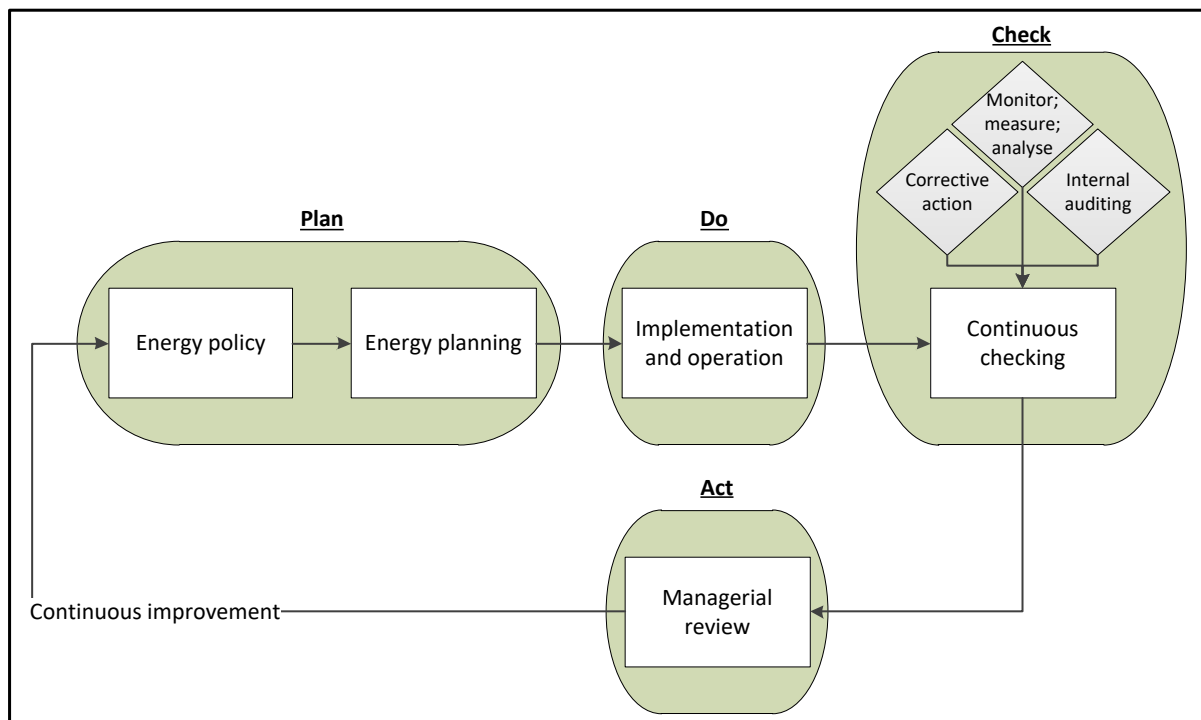


Figure 7: ISO 50001 framework (adapted from [80] and [85])

The other important components of this approach are to perform proper planning when starting with energy management on a facility, and to stipulate the goals of the implementation [83]. These goals must be communicated to all involved parties and be defined in the energy policy to ensure that all parties are aware of the steps that are to be taken [83]. After properly evaluating and planning the approach, it has to be implemented on the facility [83]. The implementation should be monitored regularly and the performance analysed [83]. This ensures that deviation from the expected performance is identified and that corrective action is planned [83]. The last part is to act on the findings and to adapt accordingly [83].

Due to the wide variety of organisations that can implement ISO 50001, the description of the approach is generalised. Several studies have focused on developing step-by-step

implementation guidelines for specific industries and their conditions [24, 46, 86, 91]. One of these studies is the framework developed by Breytenbach [24] for reducing electricity costs in the South African steelmaking industry. Although this study focuses only on electricity cost reduction, it does provide valuable inputs towards general energy management in the steelmaking industry [24].

Breytenbach [24]

The basic elements of the framework developed by Breytenbach [24] are:

- Establishing facility engagement and planning the implementation of the framework;
- Identifying the role players critical to the framework;
- Identifying the relevant operational processes and main facilities of the organisation;
- Characterising the system to gather information relevant to identifying cost saving initiatives (such as the total energy consumption, production, and layouts);
- Analysing the entire system to determine the feasibility of implementing projects by using the system characterisation in combination with the identified processes and facilities; and
- Identifying and prioritising initiatives by using all of the preceding steps.

By using the ISO 50001-based framework, Breytenbach [24] was reportedly able to identify more than R11 million of possible savings. Although there are critical differences between the focus of this thesis and the framework developed by Breytenbach [24], the inclusion of some of the elements described in his framework will be beneficial. One of these elements is the approach towards prioritisation of initiatives, as discussed in Section 2.5.2.

Schulze *et al.* [84]

Schulze *et al.* [84] presents a similar approach to energy management in industry. According to this study, there is a large energy efficiency potential that needs to be exploited, with energy management being a promising means of achieving this [84]. The study indicates that the most benefit can be obtained from energy management if the latest technology is also implemented at the facility [84]. The main components of the framework developed by Schulze *et al.* [84] relevant to this thesis are listed below:

- Planning
 - Compiling an energy policy
 - Developing an energy strategy and setting energy targets
 - Developing an action plan
 - Planning for energy risk management

- Implementation
 - Implementing the identified initiatives
 - Making decisions on required investments
 - Regularly performing energy audits
- Controlling
 - Collecting data and monitoring performance
 - Evaluating performance and acting accordingly
 - Benchmarking equipment and performance
 - Feedback reporting

Apart from the components listed above, the framework also includes steps to ensure involvement from top management, and reviewing the policies and procedures of the organisation [84]. Several components used in this framework are similar to that proposed by ISO 50001, and can be used as part of the methodology.

The development of the methodology will include using an ISO 50001-based strategy to implement the initiative of the facility. Aspects of the PDCA approach will be used to address resistance from personnel in marginally profitable facilities. By using such an approach rather than automated solutions, the general concerns raised by personnel will be addressed.

2.5.4. ENERGY AWARENESS TECHNIQUES: FEEDBACK AND REPORTING

Summary

Different methods used for energy awareness were evaluated for inclusion in the methodology. A few of these studies are evaluated in Table 10, with the most relevant thereof discussed below.

Table 10: Energy awareness techniques literature survey summary

Author	Focused on energy management	Practical application on a facility	Solution can be adapted for another facility	Integration of energy sources	Application on a South African case study	Limited use of automated solutions	Provides real-time solutions	Provide retrospective information
Goosen [88]	✓	✓	✓		✓			✓
Maneschijn [44]	✓	✓	✓		✓		✓	
Pelser <i>et al.</i> [83]	✓	✓	✓	✓	✓	✓		✓
Sono [93]					✓			

Goosen [88]

The awareness-based approach/ISO 50001-based implementation strategy was chosen due to several limiting factors. According to Goosen [88], however, manual reporting costs a great deal of man-hours, and automated reporting systems are recommended when performing energy awareness. Goosen [88] used the previously discussed PDCA approach of ISO 50001 when implementing an automated feedback reporting system for demand-side management projects on compressed air systems at mines. The method proved to be effective, and resulted in improved performance compared with manual reporting solutions [88].

Maneschijn [44]

The study by Maneschijn [44] discussed in Section 2.2.3 also used an ISO 50001-based approach, and provided operators at a cement plant with real-time updated information. The information was focused on making operators aware of the load shifting potential, and suggesting adjustments to their planned schedules [44]. This approach enabled operators to still maintain control over the system while being informed automatically of opportunities that arise, and how the opportunities can be utilised [44].

A description of the risks associated with utilising the opportunities is an important factor to include in such a system [44]. For example, at the cement plant used in Maneschijn's [44] study, information was provided on the effect that changes could have on stock levels. These studies indicate that it is possible to use automated solutions to reduce the man-hours used for reporting, while still maintaining manual control over production planning. Awareness-based assistive tools are suggested for use in the development of the methodology, and will serve as a compromise between man-hour losses and automation of systems.

Pelser *et al.* [83]

The study conducted by Pelser *et al.* [83] was briefly discussed in Section 2.5.2. It is also based on the concept of ISO 50001 on a cement plant to improve profitability. The approach by Pelser *et al.* [83] focused on first identifying the various components on the plant and the available data for the different components. Thereafter, the data was collected at a central point, from where reports could be generated and distributed to different plant personnel [83, 91]. The reports distributed by the study focused on translating the available data into usable information, and automatically distributing the reports to a predefined distribution list [83, 91]. The reports were used to identify opportunities by focusing on the following:

- Breakdown of the largest energy consumers (comparing identified key performance indicators);
- Feedback on the cost and consumption of energy sources;
- Feedback on production performance versus targets;
- Indication of missed opportunities; and
- Power consumption and cost profiles for predefined reporting periods [83, 91].

The specific methods used for reporting in this thesis will differ from those used in the cement industry, but the inclusion of these concepts will be beneficial. Pelser *et al.* [83] reported that it was possible for the cement plant to improve its profitability after implementation by minimising risks and utilising opportunities identified from the reports.

Sono [93]

A questionnaire-based data collection survey on a plant in the steel industry was conducted by Sono [93] to evaluate the effect that feedback has on empowering lower-level employees to improve performance. Based on the participation of about 60% of lower-level employees, it was found that feedback on tasks has the potential to be an effective tool for empowering employees [93]. This valuable information should be used as part of the methodology in this thesis. Feedback should include lower-level employees and should resultantly consider their understanding of awareness tools.

2.5.5. BENEFIT QUANTIFICATION METHODS

Summary

Benefit quantification methods will be required for the development of the methodology to evaluate the potential of initiatives and the effect thereof. This will also become relevant for the dynamic prioritisation of implemented initiatives. Existing studies were evaluated in Table

11 based on the provided criteria. The most relevant of these studies are discussed in more detail in this sub-section.

Table 11: Benefit quantification literature survey summary

Author	Provides baseline methods	Provides assessment methods	Provides real-time solutions	Methods applicable to various initiatives	Methods applicable to various energy sources	Provides simple quantification methods	Applicable to energy and production	Applicable to steel production planning
Booyesen [94]	✓	✓		✓	✓	✓	✓	
Hasabeigi <i>et al.</i> [95]		✓			✓	✓	✓	✓
Salahi <i>et al.</i> [96]		✓				✓	✓	✓
Worrel <i>et al.</i> [97]		✓		✓	✓	✓	✓	✓

Hasabeigi *et al.* [95]

A study conducted by Hasabeigi *et al.* [95] compared the energy use for production and resultantly the energy intensity of the iron and steel industries in China and the US. The study mainly compared the energy intensities (energy consumption per tonne production) for steelmaking facilities in the two countries [95]. This study serves as an indication of the key performance indicator that energy intensity is for the industry, which can be used for benefit quantification purposes [95].

Worrel *et al.* [97]

Worrel *et al.* [97] evaluated the energy intensity of steelmaking facilities in seven countries. From this study, three basic elements were identified for consideration when evaluating the energy use of steelmaking facilities:

- Activity: Energy use of the facility is dependent on the purpose of the plant (i.e. what is being produced);
- Structural factors: This includes the types of product that the facility produces, as well as the main process followed to produce these products; and
- Energy intensity: Energy intensity can be analysed by both economic energy intensity (energy consumption per cost) and specific energy consumption (energy consumed per amount of product produced) [97].

From this study it is important to note that the identification and understanding of the facility are critical for identifying, implementing and quantifying initiatives focused on energy improvements [97].

Salahi *et al.* [96]

Energy performance is measured by Salahi *et al.* [96] by using the definition of *specific energy*, which consists of measuring energy consumption per production output. This is then used as a consideration in production planning to improve *energy-aware* production planning [96]. The use of varying electricity tariffs to reduce energy costs is also evaluated by Salahi *et al.* [96] who find that it is effective to reflect the production rate, energy demand and electricity price throughout the hours of the day on the same graph. This provides a graphical representation of how differences in production affect energy costs, which can be included as a useful tool in the case study of this thesis.

Booyesen [94]

Research was conducted by Booyesen [94] on measurement and verification (M&V) methods in industrial projects. Existing M&V methods were evaluated, and new methodologies were presented to simplify the practical implementation of M&V processes [94]. Booyesen [94] considered M&V guides such as The International Performance Measurement and Verification Protocol [98] and the Federal Energy Management Program [99]. A shortcoming of the existing methods was found to be the lack of practical implementation guidelines, which was addressed by the method developed by Booyesen [94].

The development of this study for industrial applications makes it especially relevant to this thesis, and the methods developed will be discussed in more detail [94]. Based on Booyesen's [94] research, the core practical steps to be considered when performing M&V are:

- An evaluation of the quality of the baseline data set;
- The development and evaluation of a baseline model; and
- Performance assessment and tracking.

The selection of the baseline data set depends on the specific application [94]. According to M&V guidelines, a baseline period of three consecutive months serves as an acceptable sample of operations prior to the initiative [94]. However, it is indicated that cyclic operational variance should be considered, which might require an extension of the baseline period [94]. A 12-month data set, for example, might be required if seasonal effects have to be considered [94].

In terms of the development and evaluation of a baseline model, three types of baseline method are discussed [94]. The first of these methods is a constant baseline model, which is considered to be effective in systems with consistent operation [94]. Such a model uses an average power profile for different operational models (for example, days of the week or seasons), which is never adjusted to compensate for any changes [94]. According to Booyesen [94], the constant baseline model lacks the ability to accurately quantify the benefit of a system with fluctuating operation.

The next baseline method compensates for fluctuating operations, and is referred to as an energy-neutral baseline model [94]. The baseline is developed on the same concept as the constant baseline model, but uses energy consumption to adjust the model [94]. The shape of the baseline profile is resultantly kept the same with only the amplitude varying depending on current operations [94]. A service level adjustment is used to scale the original baseline, as per Equation 2 [94].

Equation 2: Calculation of service level adjustment for energy-neutral scaling [94]

$$\text{Service level adjustment} = \frac{\text{Energy consumption of actual profile}}{\text{Energy consumption of original baseline}}$$

The service level adjustment can then be used to adjust all the data points in the original baseline profile by using Equation 3 [94].

Equation 3: Adjusted baseline using service level adjustment [94]

$$\text{Adjusted baseline} = \text{Original baseline} \times \text{Service level adjustment}$$

An example of energy-neutral baseline scaling is presented in Figure 8, as adapted from an example presented by Booyesen [94]. This figure shows that the adjusted baseline has the same shape as the original baseline, but that the amplitude is reduced due to the total daily energy in the actual profile being lower than that of the original baseline [94]. This example uses daily energy-neutral scaling by using the total daily energy consumption [94]. It is, however, also possible to use a different reference point, such as a specific sample in the day (i.e. a few hours), or even a longer period (such as a week or month) [94].

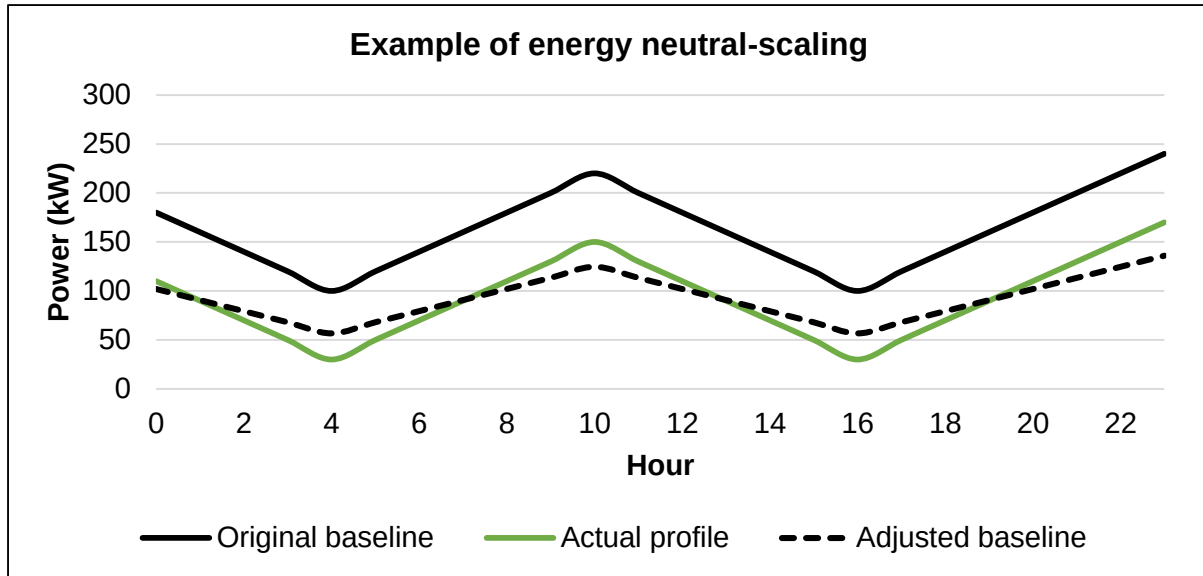


Figure 8: Example of energy-neutral baseline scaling

The last baseline method discussed by Booyesen is the regression baseline model [94]. This model adapts the baseline based on operational factors, but can use any variable in the system to scale the baseline, whereas the energy-neutral baseline model only used energy as a scaling factor [94]. This means that a variable that causes a change in power consumption (such as production or temperature) can be used to scale the total energy consumption [94]. An example of a regression baseline model is presented in Figure 9 [94].

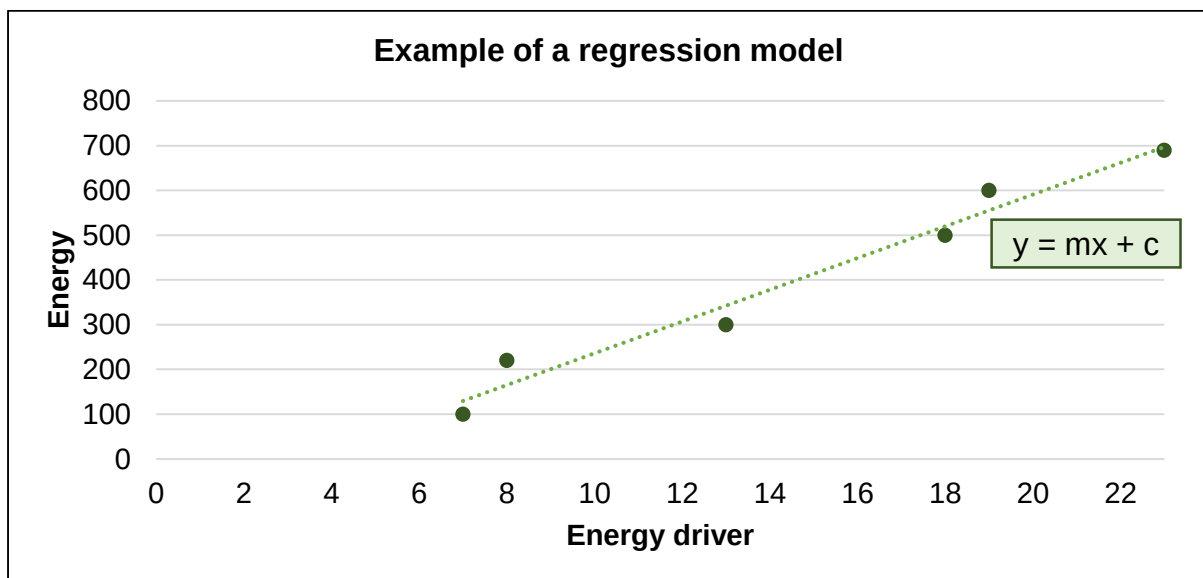


Figure 9: Example of a regression baseline model [94]

The example presented in Figure 9 shows that a regression line can be drawn based on the available data points [94]. The regression line in the example is generated based on a linear correlation, using the formula for a straight line, as per Equation 4 [94]. A different type of line

(such as a polynomial line) can also be used depending on the appropriate relationship between the variables.

Equation 4: Straight line formula used in the regression model example [84]

$$y = mx + c$$

Booyesen [94] also discusses the statistical indicators that should be used in conjunction with this method to indicate the validity of the line chosen to represent the data set. The most relevant indicator for use in this thesis is the coefficient of determination (R^2), of which the value should preferably be higher than 0.75 [94]. The calculation of the R^2 value will not be discussed in this thesis as it can be obtained by using the RSQ function in Microsoft Excel™. This function uses the available values for the x-axis and y-axis as inputs.

The last aspect of benefit quantification discussed by Booyesen [94] is the calculation of the impact by an initiative. Different methods of calculating and presenting results are discussed, but the main component required for this thesis is the calculation to determine the impact, as provided in Equation 5 [94]. In Equation 5, the baseline refers to the adjusted baseline, whereas baseline adjustment refers to any routine or non-routine adjustment that might be required due to external factors [94].

Equation 5: Calculation of the impact of an initiative [94]

$$\text{Impact of initiative} = (\text{Baseline} - \text{Assessment}) \pm \text{Baseline adjustment}$$

2.6. CONCLUSION

This chapter served as the literature review of the thesis. It started with a description of steel production planning procedures and a review of energy focused production planning approaches in other industries. This was followed by a detailed discussion of the most relevant studies evaluated in Chapter 1 to support the formulated novel contributions. The discussion was followed by the identification of possible steel production planning initiatives to be used as part of the methodology. Lastly, existing solutions that can be used to construct the different steps in the methodology were evaluated and discussed. The information gained in this chapter can now be used to develop the methodology.

Chapter 3: Methodology

A new integrated cost model for steel production planning is developed in this chapter. The reader is equipped with the necessary information to apply the model to a steelmaking facility.

3. DEVELOPMENT OF AN INTEGRATED COST MODEL FOR STEEL PRODUCTION PLANNING

3.1. INTRODUCTION

This chapter focuses on developing the methodology to solve the problem identified in Chapter 1 by using the research conducted in Chapter 2. The purpose is to realise cost savings on a steelmaking facility by focusing on production planning. From literature it was determined that this will be done by adapting and integrating existing solutions and initiatives. Cost savings will be realised by adapting production planning to improve energy and production cost efficiencies. Several existing solutions to be used to develop the model were discussed in Chapter 2; these solutions will be integrated during the development of the methodology. The relevance of the methodology to the novel contributions will also be discussed.

3.2. INTEGRATED COST MODEL FOR STEEL PRODUCTION PLANNING

3.2.1. PREAMBLE

The previous chapter evaluated several existing solutions from literature to be used as part of the integrated cost model for steel production planning. Figure 10 indicates how these existing solutions are used in the development of the solution. The existing solutions are adapted and integrated for use in the integrated cost model. The methodology in Figure 10 is a simplified version of the methodology developed in this chapter. Figure 10 indicates how existing solutions are used to construct the simplified methodology. The development of the methodology is discussed at the hand of the five steps in the simplified methodology.

The basic concept of the cost model is to identify, evaluate, compare and prioritise, implement, and integrate initiatives by focusing on steel production planning. Each step is discussed in detail at the hand of an extended methodology. Step 2 and Step 4 in Figure 10 take place for initiatives individually, while the other steps take place for all initiatives at the same time. The integration of implemented initiatives focuses on the dynamic prioritisation thereof based on expected benefit calculations. The purpose of the integration is to achieve a larger cost benefit by implementing several initiatives on the same facility, even though they have interactive effects on one another.

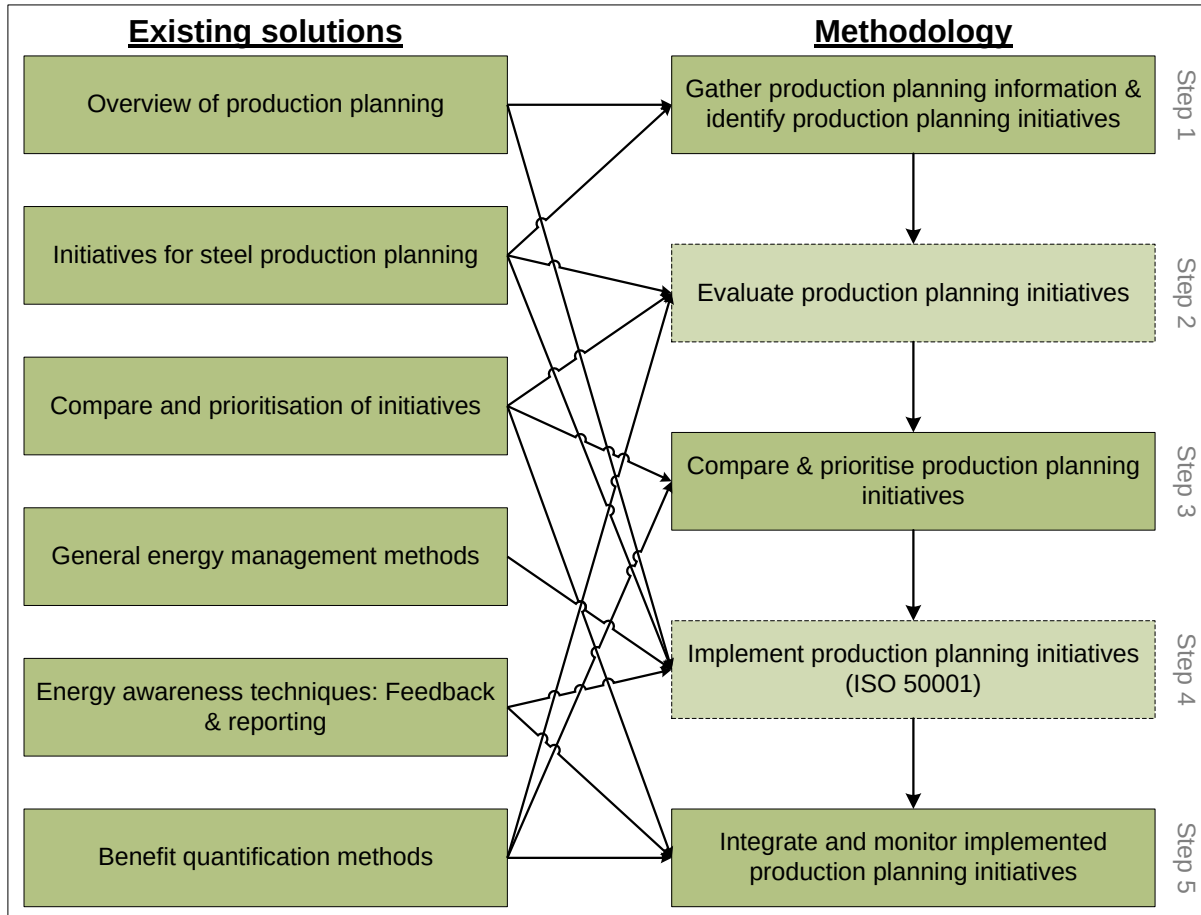


Figure 10: Development of the simplified methodology using existing solution

Step 1 in the simplified cost model of Figure 10 is gathering the production planning information and gaining an understanding of how information is distributed and used on the facility. Once the basic process and functions of different parties involved with the production planning process are understood, initiatives are identified for the facility from literature and discussions with plant personnel. During Step 2, each initiative is evaluated and characterised individually. This is followed by a comparison of the initiatives during Step 3, based on the previous evaluation. The comparison is used to prioritise the order for implementing initiatives. This is considered to be a static prioritisation as it only occurs once during Step 3.

Once it has been decided in which order to implement initiatives, the initiatives are considered separately again for the practical implementation using Step 4. This implementation is based on the PDCA approach of ISO 50001, which ensures that initiatives are adapted, implemented, monitored and revised separately. Lastly, the initiatives are integrated during Step 5, which mainly consists of the dynamic prioritisation thereof. This ensures that the most beneficial scenario occurs. Restrictions that one initiative has on another are considered during the integration.

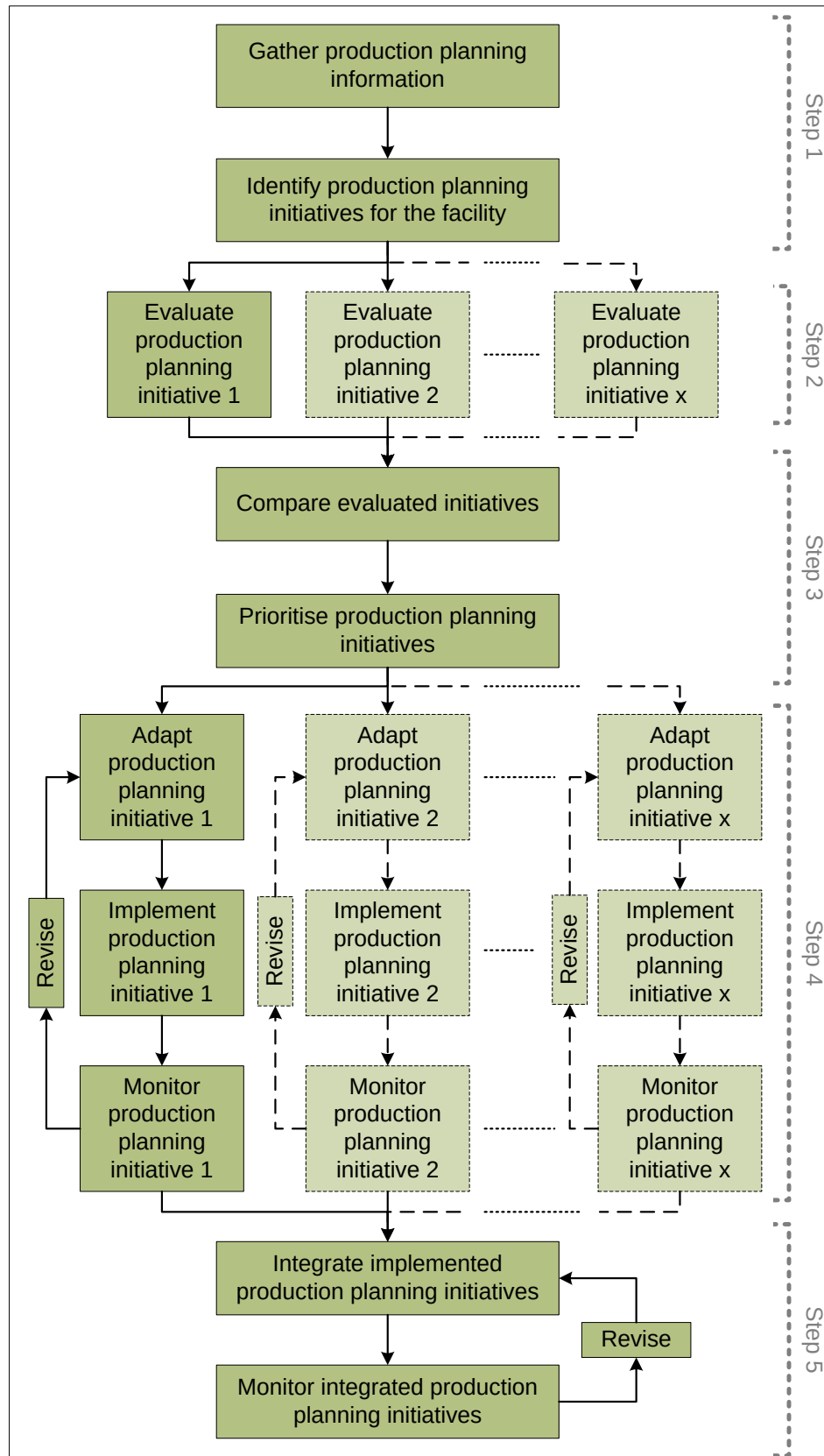


Figure 11: Integrated cost model for steel production planning

The developed methodology uses ISO 50001-based implementation strategies to improve production planning regarding the reduction of energy costs, without affecting production negatively. It was decided to use an ISO 50001-based implementation strategy to mitigate the practical implementation constraints described by Contribution 3 in Section 1.4. The methodology is developed in such a way that it is adaptable to other production planning processes in steelmaking facilities and other industries.

The use of an integrated approach is critical as it provides the facility with the opportunity to benefit from more than one initiative. The lack of an integrated approach is expected to result in the facility only implementing the highest prioritised initiative identified in Step 3 (Figure 10). There will therefore only be benefits from one initiative. A detailed version of the integrated cost model is presented in Figure 11, which is discussed in the remainder of this chapter.

3.2.2. STEP 1: GATHER PRODUCTION PLANNING INFORMATION AND IDENTIFY PRODUCTION PLANNING INITIATIVES

Gather production planning information

This step consists of gathering production planning information. During this step, the continual collection of information used and provided by production planners has to be set up, as this information is used during the implementation of the methodology. Basic elements to consider in a production planning environment were suggested in Section 2.2.3. The following should be familiarised for the specific facility:

- Forecasts for production;
- Maintenance procedures and intervals;
- Equipment reliability and capabilities;
- Energy consumption of sections and equipment; and
- The availability of buffers in the system.

The basic process and its different entities as described by Lin *et al.* [23] were discussed in Section 2.2.2 (Figure 6). Based on this discussion, a conceptual overview of production planning with regarding the different sections of a steelmaking facility was constructed, as presented in Figure 12. As per this overview, orders are provided to production planners as an input. It is then the responsibility of production planners to regulate the steel plant, stockyard and primary rolling sections. The end purpose is to ensure that the requirements of dispatch and secondary rolling are met.

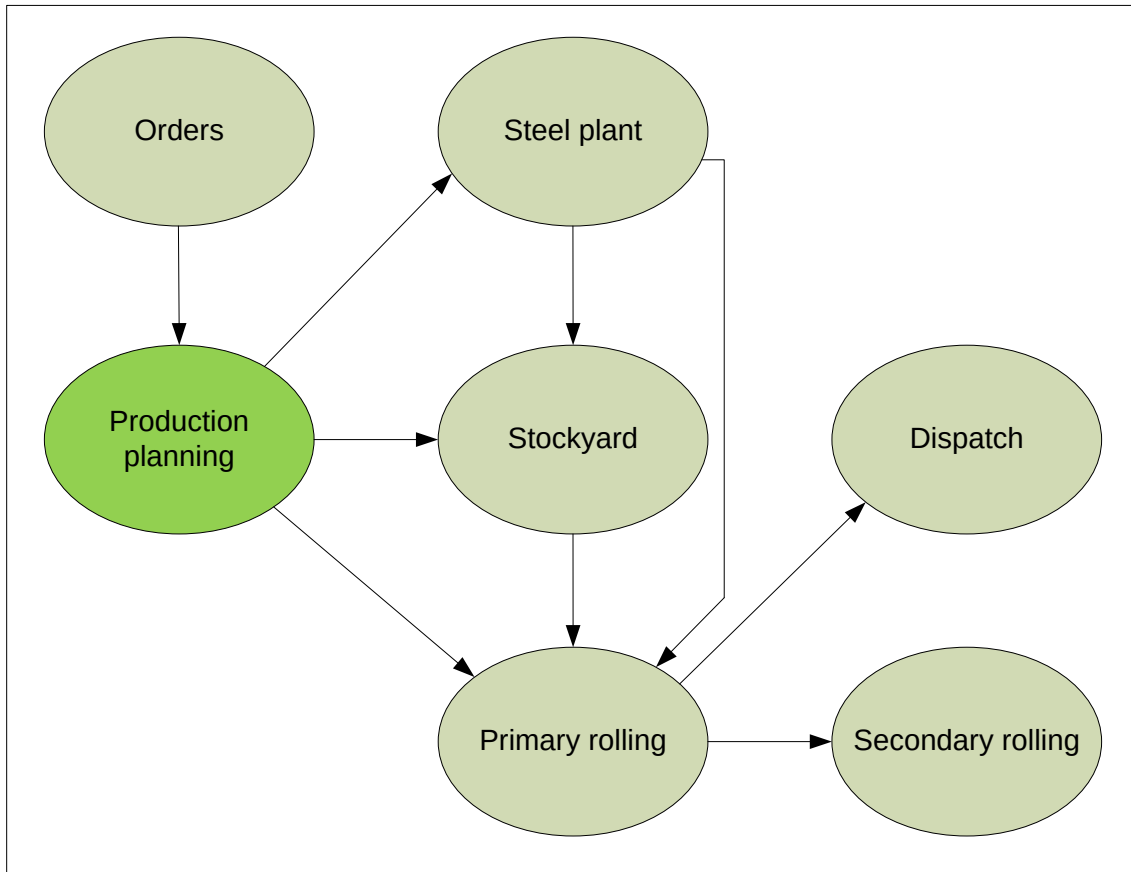


Figure 12: Conceptual overview of production planning relative to different sections

The previously discussed elements for consideration in production planning were adapted and integrated with the overview provided in Figure 12. This makes it possible to consider such elements and provide tools for production planners, as presented in Figure 13. This figure summarises the purpose of the integrated cost model. The factors to be considered are:

- Delivery dates for orders received from clients;
- Steel qualities to be casted;
- Required profiles to be rolled by the primary rolling mill; and
- The stock level at the time.

This is also the basic production planning information that should be collected and adapted by the cost model. The outputs provided by the optimised cost model, as indicated in Figure 13, are summarised below:

- Feedback and reporting for different sections and the production planning department; and
- A model integrating the different sections with production planning.

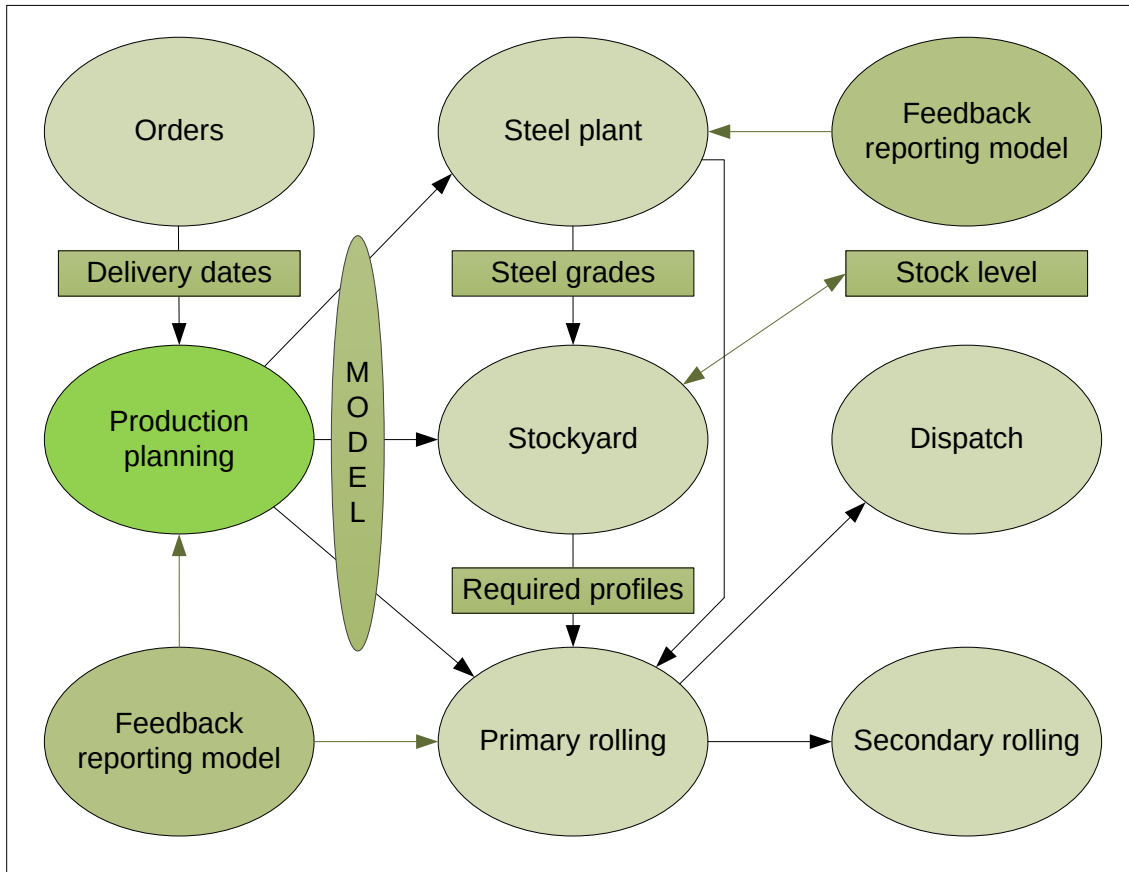


Figure 13: Conceptual overview of production planning to be achieved by the model

Identify production planning initiatives for the facility

Once the process of production planning on the specific facility is understood, initiatives to be implemented on the facility should be identified. Steel production planning initiatives are identified by using previously implemented concepts/initiatives from literature. Such initiatives have to be adapted to be relevant to the specific facility, but the basic concept and general approach of previous implementations serve as a valuable guideline. For this thesis, the initiatives of a steelmaking facility were identified using the BF-BOF process in Section 2.4. The relevant initiatives that were identified from literature are described in Table 12.

Table 12: Basic description of identified initiatives

Initiative	Description
Hot charging of the primary rolling mill furnace	Hot charging casted steel into the primary rolling mill furnace when possible. If this is already done, it can be attempted to improve/increase the amount of hot charging that takes place.
Ladle furnace load shifting	Reducing power consumption of ladle furnaces during peak tariff times by processing less energy intensive steel qualities during such periods.
Ladle and crane time loss reduction	Reducing time losses between the concast and preceding processes by the improved scheduling of cranes to be used for transport, and ladles to be used for heating.
Primary rolling mill apportionment model	Arranging of blooms with similar specifications and thermal performance together in the furnace to improve heating quality.
Primary rolling mill load shifting	Reducing power consumption of the motors of the primary rolling mill during peak tariff times by rolling less energy intensive steel or delaying operations during such periods.

3.2.3. STEP 2: EVALUATE PRODUCTION PLANNING INITIATIVES

Overview

The purpose of evaluating the identified initiatives is to determine their individual feasibility. Each initiative is evaluated separately by using Steps E.1–E.5, which are presented in Figure 14. Once an initiative has been evaluated, it will be compared with other identified initiatives and be prioritised for implementation. The findings from the steps in Figure 14 are used to compare and prioritise initiatives. To make this possible, the initiatives are categorised according to a criterion in each step. The five steps in Figure 14 are discussed in more detail along with the categorisation options.

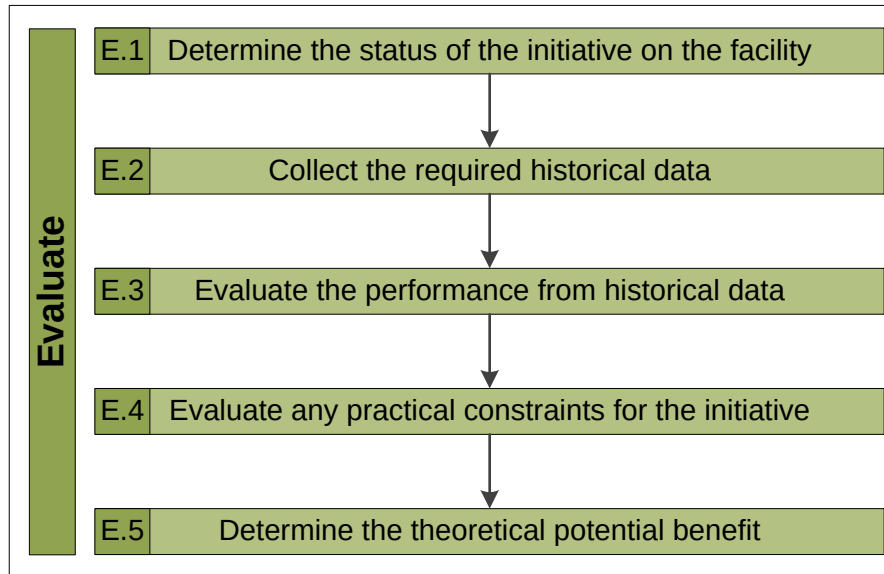


Figure 14: Steps for evaluating a production planning initiative

Step E.1: Determine the status of the initiative on the facility

Once a production planning initiative has been identified, it is important to determine the status of the initiative on the specific facility. It is possible that the initiative has already been implemented, or that it has been attempted in the past. Such information will be important to determine the possible constraints that could restrict its implementation. If the initiative has been attempted in the past but was unsuccessful, it could be an indication of a lack of scope on the facility.

It is critical to obtain the intuitive opinions of plant personnel regarding the possibility of implementing the initiative, and to identify the critical parties who will be involved. It must be determined what could restrict the initiative, and what the reasons for possible resistance could be. The categories in which the status of an initiative is placed are as listed below:

- The initiative is already implemented successfully on the facility;
- The initiative was attempted previously, but could not be implemented successfully;
- The initiative is already implemented, but is not as effective as expected; and
- The initiative was not considered previously.

Step E.2: Collect the required historical data

All relevant data must be collected to determine the feasibility of the identified initiative on the specific facility. The already gathered production planning information is used during this step, but it might not be sufficient for evaluating the feasibility of the initiative. The required data that needs to be collected varies for each initiative, and has to be identified by gaining an

understanding of the facility and initiative. The purpose of the initiative is to adapt production planning for improved energy and production efficiencies. Collected data sets should therefore at least include production, energy and cost data to evaluate the potential for such improvements.

As per the research conducted by Booysen [94], discussed in Section 2.5.4, it is critical to collect data that represents a variety of scenarios, such as different seasons, production needs and economic circumstances. The data collected in this step will be relevant later for compiling a baseline and assessment method for the initiative. The different types of baseline option discussed by Booysen [94] should be considered when evaluating data requirements. Data must preferably be available on a continual and sustainable basis when used for implementation or assessment purposes.

Production planning involves several entities, such as the production planners, production schedulers, and plant personnel responsible for production to take place practically. It is important to focus on all entities and to collect relevant data accordingly. Data can be a powerful tool when analysed accurately and communicated to critical target groups. The categories in which data collection can be placed to evaluate and compare initiatives are:

- None of the desired data is available;
- Some of the desired data is available selectively;
- The data is available, but cannot be obtained sustainably on a regular basis; and
- All of the desired data is sustainably available.

Step E.3: Evaluate the performance from historical data

The approach for analysing the collected data depends on the specific initiative and the status thereof on the facility. The evaluation of data includes determining how production and energy consumption differ for various scenarios relevant to the initiative. This indicates the flexibility for changes in the production planning approach to implement the initiative. Once the historical data has been evaluated, it becomes clear whether it is feasible to implement the initiative from a theoretical point of view.

Identifying different conditions from historical data serves as an indication of the possible effect that the initiative can have, and what scenarios provide the highest benefit. As part of the analysis, certain data points should be isolated and evaluated to simulate the possible effect of the initiative. This will highlight the ideal conditions for implementation and should be recreated. One example is to evaluate the amount of variation that exists between the energy consumption of different steel qualities at the ladle furnaces.

The involved parties identified in Step E.1 must be kept in mind when analysing data. It is important to present data to the target groups in a sensible manner depending on their skill levels and the concerns that they might have raised. This must also be considered when theoretical benefits are calculated in Step E.5. The categories in which the performance from historical data are placed are listed below:

- There is no variation between different scenarios in the historical data;
- There is limited variation observed between different scenarios;
- There is the possibility of creating scenarios where variation exists; and
- There is sufficient variation between scenarios to achieve benefits from the initiative.

Step E.4: Evaluate any practical constraints for the initiative

After establishing that there is sufficient variation between scenarios for an initiative, the next step is to evaluate the practical constraints for implementation. This was already done to a certain extent when the status of the initiative on the facility was determined in Step E.1, but the constraints to be evaluated critically to determine the requirements for implementation. It is also important to re-evaluate constraints that may have occurred in the past to determine whether they are still relevant. New constraints due to changing conditions also have to be evaluated. The different scenarios evaluated from data in Step E.3 serves as an indication of which conditions would restrict the performance of the initiative.

After identifying such constraints, it is critical to investigate ways in which performance can be maintained during such conditions, or to consider methods to minimise the occurrence thereof. As part of identifying the practical constraints for the initiative, it is vital to discuss the concept thereof with all entities. The process used when planning production must be understood, and the relevant constraints need to be identified. This step uses the information obtained in Step E.1 as the reasons for not previously implementing the initiative will highlight several constraining factors.

The elimination of practical constraints is the focus area for the implementation of initiatives as it reduces the restricting scenarios and maximises the benefits. The solution should focus on either mitigating or eliminating practical constraints. Apart from practical constraints in the processes, the infrastructural practical constraints of the facility need to be considered. Due to the struggling conditions of facilities in South Africa, initiatives requiring little to no capital are preferable. The categories in which the practical constraints should be classified are:

- Practical constraints cannot be mitigated (infrastructure and process related);
- Capital is required to mitigate the constraints;

- It is possible to implement the initiative, but excessive resistance from plant personnel exists; and
- Little to no practical constraints exist.

Step E.5: Determine the theoretical potential benefit

The last step that is part of the *evaluate* section of the methodology is determining the theoretical potential benefit of implementing an initiative. This is done based on the historical performance evaluated in Step E.3 and the practical constraints in Step E.4. The amount of variation that exists and the possibility of replicating such variations as desired serve as an indication of the theoretical potential benefit of an initiative.

The quantification of the theoretical benefit is not only used to determine the feasibility of the initiative. To motivate changes to production planning methods, the benefit has to be stipulated. If several initiatives have to be implemented, these initiatives will have to be integrated. It is possible that conditions can only allow one initiative to be implemented at a time, in which case the real-time benefits have to be predicted and compared using the available inputs. This can be used to determine which initiatives should be prioritised at a given time during the dynamic prioritisation of the integration step (Step 5 in Figure 10) in the methodology.

Energy and production benefit quantification must be considered when developing these methods. Methods used to determine the theoretical potential benefit should be adaptable to dynamic benefit quantification. The methods used for benefit quantification should consider the different scenarios identified in Step E.2 and quantify the benefit based on historical data. Theoretical benefits for different scenarios also serve as an indication of which aspects to focus on to achieve benefits.

The categories in which the calculated theoretical benefit can be classified for the evaluation and comparison of initiatives are listed below:

- No potential exists to achieve any benefit from the initiative on the facility;
- Potential does exist for the initiative, but it is very limited;
- Benefits will sometimes be seen, if conditions allow them; and
- Potential exists and can be utilised.

3.2.4. STEP 3: COMPARE AND PRIORITISE PRODUCTION PLANNING INITIATIVES

Compare evaluated initiatives

After the individual evaluation of each identified initiative, the findings for the different initiatives need to be compared. The last output of the evaluation was to determine a theoretical benefit for each initiative. The comparison determines the initiative that provides the largest financial benefit. This is, however, not the only contributing factor when prioritising initiatives. Each step was provided with a list of categories in which findings should be classified. These categories are now used as part of the comparison and prioritisation of initiatives.

This criteria is an adaption of the concept presented by Breytenbach [24]. Values are allocated to each category, as indicated in Table 13. An initiative ranking value is resultantly allocated to each initiative by classifying every step of the evaluation in one of the categories. Negative values are allocated to the least favourable category (two leftmost columns), and a higher value to the most favourable category (rightmost column).

Table 13: Value allocation of evaluation steps for initiative ranking

Step	Description	-2	-1	0	2
E.1	Status	Successfully implemented	Previous unsuccessful attempt	Implemented, but ineffective	Not previously considered
E.2	Data availability	No data available	Selective data available	All data unsustainable available	All data sustainably available
E.3	Historical performance	No variation	Limited variation	Possible variation	Sufficient variation
E.4	Practical constraints	Cannot be mitigated	Capital required	Resistance exists	Few constraints exist
E.5	Potential benefit	No potential	Limited potential	Achieved if conditions allow it	Potential benefits exist

After allocating an initiative to the relevant category, the initiative ranking value is calculated using Equation 6. This is adapted from the concept of the calculation used by Breytenbach [24]. In this equation, all values are added together, but the ratings for Step E.4 (practical constraints) and Step E.5 (potential benefit) are doubled. This is due to the critical role that these aspects play in the successful implementation of the initiative.

Equation 6: Initiative ranking calculation for the comparison of initiatives

$$\text{Initiative ranking} = E.1 + E.2 + E.3 + [E.4 + E.5] \times 2$$

Prioritise production planning initiatives

Step 2 of the methodology provided the required information to prioritise the implementation order of initiatives. The previous steps compared the different initiatives with relevance to the facility on which they are to be implemented. The output of the comparison is an initiative ranking value for each identified initiative. A higher ranking indicates the highest prioritised initiative. After this step, the implementation order of initiatives will be known.

3.2.5. STEP 4: IMPLEMENT PRODUCTION PLANNING INITIATIVES (ISO 50001)**Adapt production planning initiative**

After prioritising the implementation order of initiatives, the initiatives are considered separately again. The *adapt-implement-monitor-revise* steps of the methodology (Step 4; Figure 10) form part of an ISO 50001 system within the methodology, and are based on the PDCA approach. The purpose of these steps is to adapt the initiatives, which were identified from literature to be applicable to the specific conditions of the facility, and to implement the initiatives practically. The relevance of the steps in the methodology regarding ISO 50001 is presented in Figure 15. The *adapt* step represents the *plan* step of ISO 50001.

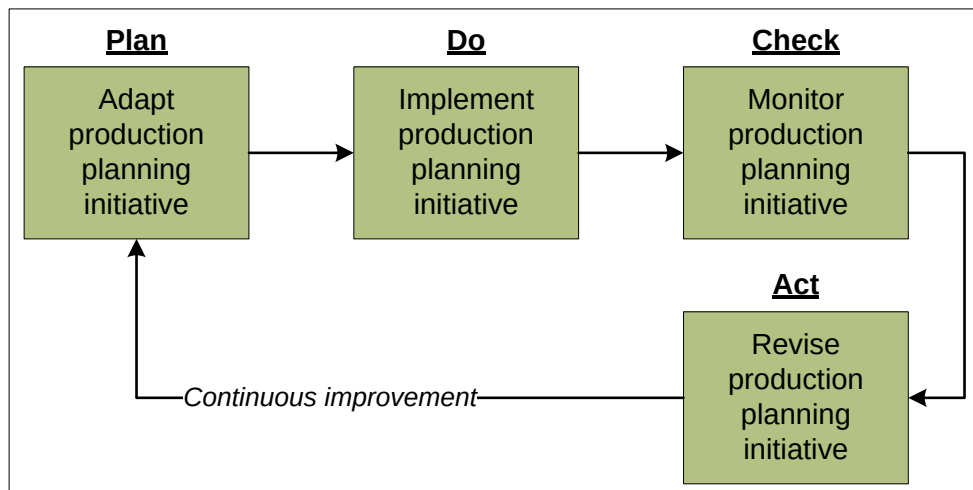


Figure 15: Implementation of the initiatives based on ISO 50001

The outcomes of this step in the methodology are as follows:

- Highlight the main differences between the initiatives identified from literature and the relevance on the specific facility;

- Discuss the changes required to adapt the initiatives identified in literature;
- Discuss the additional components that can be added to the initiatives on the facility; and
- Revisit the practical constraints identified in Step E.4, and how they affect the application of the initiative on the facility.

Implement production planning initiative

Overview

The implementation of the initiatives on the facility represents the *do* step of ISO 50001. The implementation of each individual initiative is conducted by using Steps I.1–I.4, which are presented in Figure 16. During this step of the methodology, it is troublesome to give exact solutions for each identified initiative due to the possible variations that exist between different facilities, such as the existing methods and practical constraints. General suggestions and selective examples are provided on how to implement an initiative during the discussion of the steps.

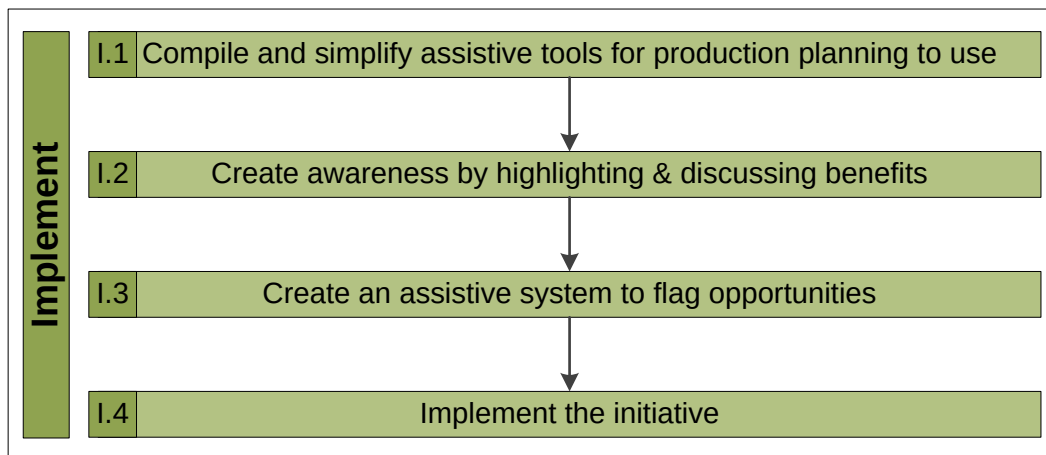


Figure 16: Steps for implementing a production planning initiative

Step I.1: Compile and simplify assistive tools for production planning to use

The first step of the implementation is to use the practical constraints identified in Step E.4 to determine which scenarios need to be mitigated. The theoretical benefits quantified in Step E.5, which indicate the theoretical potential benefits of an initiative, are also used in this step. The findings from these two steps are combined and used to develop assistive tools for production planners. As discussed in Step E.3 (evaluation of historical performance), the tools are developed to be applicable for each target group to ensure that they convey sensible information.

The theoretical benefits quantified in Step E.5 are used to highlight benefits for involved parties, which motivate them to adapt schedules to utilise these benefits. Production planners should be able to compare different scenarios and see the predicted effect that can be achieved if energy cost efficiency is included as an input for production planning. The assistive tools must be simple to use, and they should not unnecessarily increase workload. By using existing methods and tools that are already being used and by integrating certain features, the methods and tools can be included as part of the standard operating procedures. The effect and usability of the tools have to be evaluated regularly (preferably weekly), and adapted accordingly.

An example of such a tool would be to create a reference sheet for the energy intensity of different steel qualities at ladle furnaces. Production planners will use this sheet when creating the production plan to rather schedule less energy intensive steel qualities in peak periods. Depending on the available technology, an interactive interface for production planners is recommended to compare scenarios and predict the effect of planned changes.

Step I.2: Create awareness by highlighting and discussing benefits

Due to the ISO 50001-based implementation strategy of this study, a large focus of the methodology is to create awareness regarding the initiative among all involved parties. Even though only some of the entities are required when physically adapting production plans, the resulting changes will influence the actions of several entities. The changes in production planning approaches and seemingly irregular behaviour might not make sense to some parties if they are not aware of the initiatives and their benefits. It is critical to ensure that all involved parties are included in discussions, the implementation of the initiative, and feedback regarding project performance.

Benefit discussions can be approached in various manners depending on the facility and the changes that may occur as part of the solution. The type of information, and the way in which it is communicated, is dependent on the skill levels of target groups. Personnel on production facilities are typically more concerned with production benefits, and tend to neglect energy cost efficiency. This is especially the case in a country such as South Africa, where energy costs have not been a contributing factor to competitiveness in the past, as discussed in Section 1.2.2. For this reason, the effects of production and energy cost should be addressed during discussions.

Awareness must be maintained by regularly following up with the different parties regarding the status of the initiative (follow-up intervals will differ for each entity). Feedback is required

to highlight achieved benefits for different entities. This should be done by means of regular feedback reports, using the theoretical benefits calculated in Step E.5. The feedback should highlight positive as well as negative performance and missed opportunities, thus enabling different parties to determine how to improve performance. Feedback should focus on energy and production cost efficiency.

Step I.3: Create an assistive system to flag opportunities

Production planning methods typically use schedules that are distributed to several parties. These schedules are compiled by considering various factors (as discussed for Figure 13), which make it complex to fully automate some of these systems. As an ISO 50001-based implementation strategy is used, focus is not placed on automation. This approach is used because plant personnel resist automated solutions and because of capital constraints. To ensure that opportunities are utilised, however, it is suggested that opportunities be flagged for production planners as part of the implementation strategy.

The flagging system itself has to consider a variety of input factors. These factors serve as an indication of which scenarios are actually opportunities and should be flagged, and which should be ignored. The production planning process for the facility and the constraints of the process must be understood thoroughly. The inputs for production planning should be considered along with the contents of the schedule that is eventually distributed. Constraints relevant to the specific initiative (as identified during Step E.4) need to be considered to ensure that only achievable opportunities are flagged.

The flagging system should be used in conjunction with Step I.1, and form part of the production planner's daily operations by using assistive tools. Opportunities to generate ideal conditions for the initiative to be implemented should be flagged for the production planner. It has to be done in such a way that it is clearly highlighted, and that the production planner is informed of what can be done to utilise the opportunities. The flagging system must be updated regularly and adapted based on the feedback from the relevant parties (interval will depend on feedback from different parties).

As part of the flagging of opportunities, the theoretical benefits determined in Step E.5 are used to indicate the potential benefits to the production planner. The indication of a possible cost benefit of making changes to the schedule will serve as a motivation for production planners to consider implementing the flagged opportunities. Predicting the possible benefits will be required for the integration of initiatives to quantify the most beneficial situation at a given time.

An example of such a flagging system is to identify similarities between the latest production plans for the concast and the primary rolling mill. It might be that the schedules on the facility are compiled by different entities, and that they are not aware of the similarities in their schedules. If a steel quality is scheduled to be casted and rolled on the same day, it should be considered whether it is possible to hot charge the steel quality rather than to first move it to the stockyard. It sometime happens that there is stock available in the stockyard for the steel quality, and the primary mill personnel would rather obtain the steel there. This can be prevented by flagging opportunities early in advance.

Step I.4: Implement the initiative

After developing the various elements discussed in Step I.1 to Step I.3, the initiative is implemented by applying these solutions to the facility. Implementation will depend on the specific initiative, the facility and the targeted parties. Critical aspects to consider for the implementation are to ensure that the relevant parties know exactly how the systems work and what to use them for. The implementation takes place in several phases, therefore providing opportunities for the initiative to be updated and adapted according to the requirements. Regular feedback on the effect that the initiative has is also important and serves as an indication of how it can be improved (interval of feedback depends on different entities).

Monitor production planning initiative

The next part of the methodology is to monitor each initiative individually, which represents the *check* step of ISO 50001. Due to the human interference required for the implementation strategy, it is important to regularly assess the effectiveness of the methods that are used. This is done by obtaining feedback from the involved parties and comparing this feedback with actual results. If more than one initiative have been implemented, the practical benefits of all initiatives should be assessed and monitored.

The monitoring of the performance of an initiative has to be done accurately and consistently. It is therefore necessary to develop a baseline and performance assessment method to monitor the initiative. Different M&V approaches and possible baseline methodologies were suggested by Booyesen [94] in Section 2.5.4. The chosen baseline methodologies depend on the specific initiative and facility characteristics. Suggested baseline methods from the discussion by Booyesen [94] are listed in Table 14 for the identified initiatives.

Table 14: Suggested baseline methodologies for identified initiatives

Initiative	Suggested baseline methodology
Hot charging of the primary rolling mill furnace	Regression model of furnace production versus furnace energy consumption (example in Figure 9).
Ladle furnace load shifting	Energy-neutral power profile scaling (example in Figure 8).
Ladle and crane time loss reduction	Regression model of ladles moved versus moving duration (example in Figure 9).
Primary rolling mill apportionment model	Regression model of furnace production versus furnace energy consumption (example in Figure 9).
Primary rolling mill load shifting	Energy neutral power profile scaling (example in Figure 8).

The suggested baseline methods in Table 14 were chosen for the initiatives based on the general applications suggested by Booysen [94]. These suggestions should be adapted based on the specific facility and discussions with plant personnel. Selected methods should consider the effect that the initiative has on cost efficiencies, as determined from the theoretical benefits calculated in Step E.5. This feedback needs to be provided to the involved parties. The feedback forms part of the awareness creation and maintenance of Step I.2 (the interval of feedback will depend on the baseline method and involved parties).

The effectiveness of the system serves as an indication of which areas and parties require more focus, and whether the predictions made during the *evaluate* stage were accurate. If an initiative does not achieve the predicted benefit, it has to be decided whether to continue with the current approach, and how it can be adapted. Deviations from the theoretical benefit quantified in Step E.5 have to be evaluated to identify the origin. The ultimate goal of an initiative is reducing energy cost while maintaining or improving production. This performance should be monitored specifically, and serves as an indication of the success of the implemented solution.

Revise

The last part of the ISO 50001-based implementation strategy is to ensure that the system is improved continuously. This is achieved by the *act* step, which is represented by the *revise* step of the methodology. Based on the performance monitoring results as well as comparing the results with the estimated theoretical benefits, it is determined whether it is required to revise the approach for an initiative. During this step, feedback provided by plant personnel is used to address concerns. These revisions depend on the performance of an initiative on the

specific facility, and require improvisation for the adaption of the methods developed during Step I.1 to Step I.4.

3.2.6. STEP 5: INTEGRATE AND MONITOR IMPLEMENTED PRODUCTION PLANNING INITIATIVES

Integrate implemented production planning initiatives

As soon as multiple initiatives have to be implemented, these initiatives have to be integrated to ensure that the optimal benefit is used by dynamically prioritising initiatives according to their predicted benefits. The basic concept of integrating several initiatives is based on Figure 17.

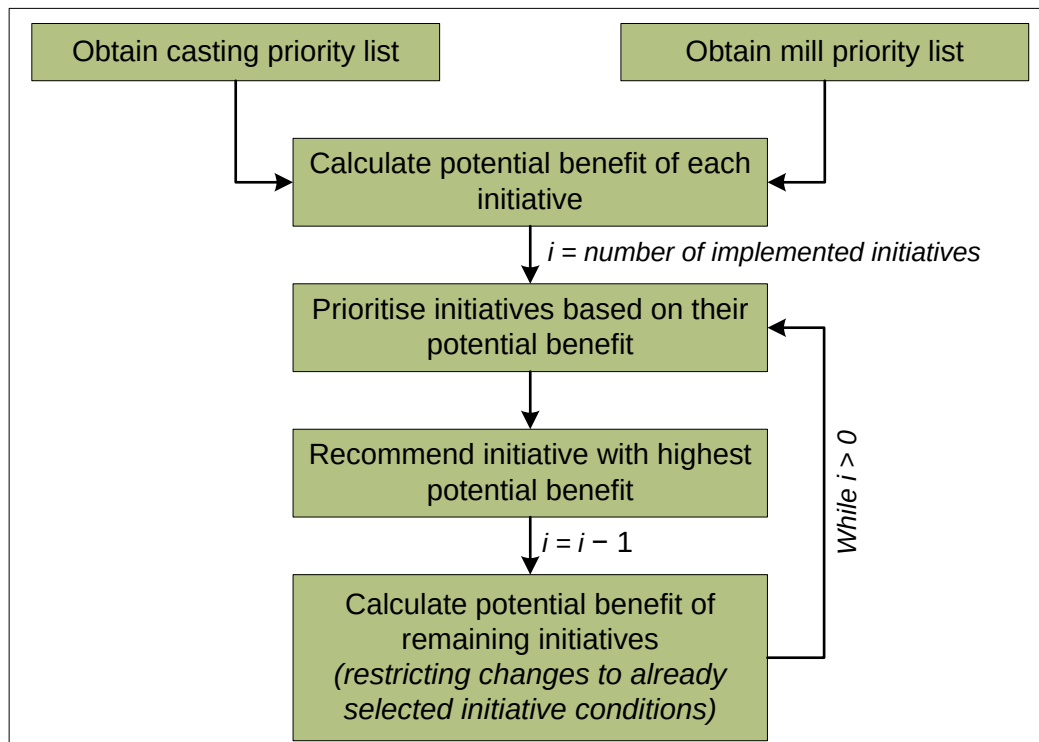


Figure 17: Integration of multiple production planning initiatives

As per Figure 17, the latest priority lists for the steelmaking and primary rolling sections are compared, and the potential benefits of each initiative are calculated. Thereafter, the initiatives are prioritised based on their theoretical potential (with i being the number of implemented initiatives). The highest prioritised initiative is recommended to the relevant parties for implementation, and the theoretical benefits of the remaining initiatives are calculated. The calculation of the theoretical benefits of the remaining initiatives has to consider the restrictions that the already prioritised initiative(s) enact on the system. Initiatives are then prioritised again, and the process is repeated until no more initiatives remain.

The integration of initiatives ensure that the most beneficial aspects of all implemented initiatives are utilised. The proposal for the most beneficial scenario should be included in the flagging system, which is used to inform production planners of how to utilise initiative benefits.

The mathematical operation of the cost model is based on Figure 17. The application thereof will differ, depending on the specific facility and the production planning initiatives that are viable for implementation at the facility. More detail on the mathematical operation and logical flow of the decision making will be provided at the hand of the case study in Section 5.2.6.

Monitor integrated production planning initiatives

As with the monitoring and evaluation of individual initiatives, it is also important to evaluate the success of the integration thereof. This step is considered to be a variation of the *check* step of ISO 50001. It is important to monitor counteractive initiatives and their performance, and to revise the approach accordingly. It is critical to provide feedback to different parties regarding the benefits of integrated initiatives. The frequency, detail and format of feedback to relevant parties depend on the intended purpose of the communication, as well as the targeted recipients.

Revise

As with the individual initiatives, regular feedback regarding the integrated approach is provided by using the *act* step of ISO 50001. During this step, feedback from plant personnel and performance monitoring of initiatives are taken into account to improve the integration of initiatives. This ensures that the system develops dynamically based on the latest performance, and that any possible concerns are addressed.

3.3. NOVEL CONTRIBUTIONS OF THE METHODOLOGY

The novel contributions of the study were formulated in Section 1.4 based on the evaluation of existing research. Figure 18 indicates how the novel contributions are addressed by the steps of the simplified methodology. Each novel contribution is discussed thereafter.

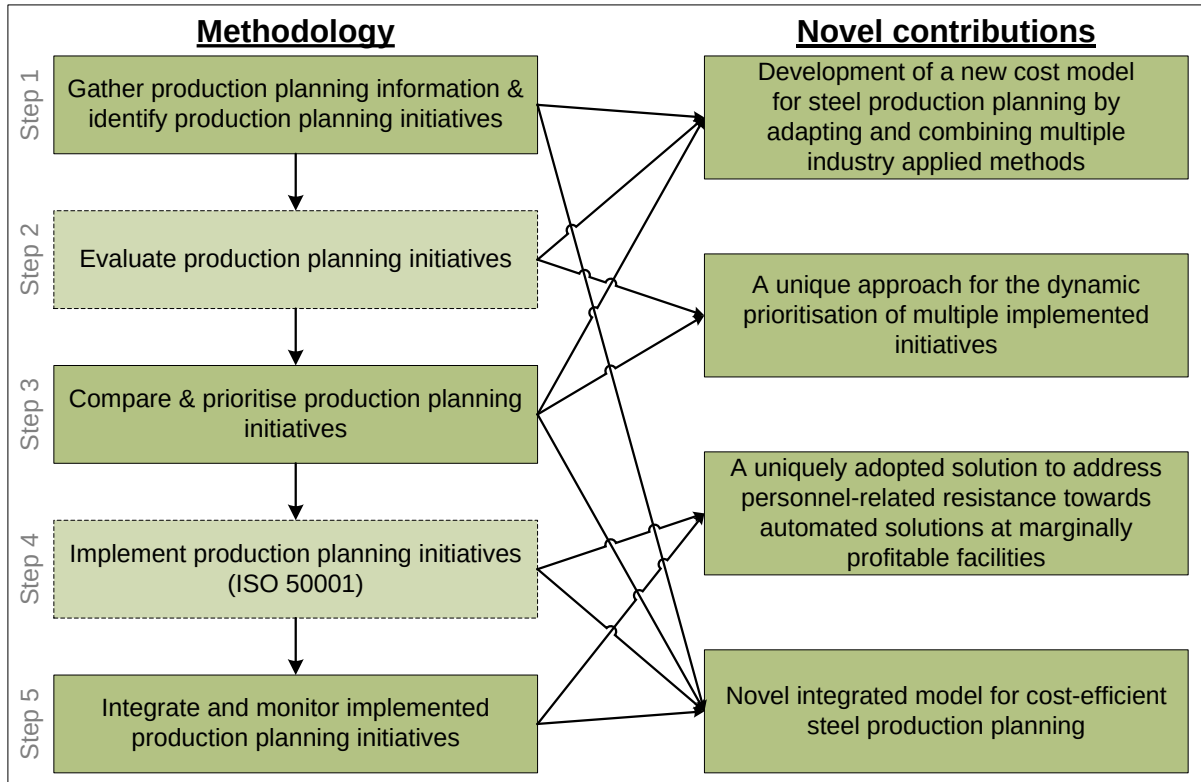


Figure 18: Evaluation of novel contributions based on the methodology

Contribution 1:

*Development of a **new cost model** for steel production planning by **adapting and combining multiple** industry applied methods*

Several initiatives were identified from literature, and listed for application as part of the methodology. The steps in the methodology present an approach to evaluate, adapt, implement, monitor and revise the individual initiatives while simultaneously comparing and prioritising them as part of the integration. The methodology adapts several existing solutions from literature to achieve this, and presents a novel integrated approach towards production planning. By using this new cost model it will be possible to develop adapted solutions for identified initiatives on a facility and to integrate them with other initiatives.

Contribution 2:

*A **unique approach** for the **dynamic prioritisation** of multiple implemented initiatives*

The first utilisation of benefit quantification in the methodology is in Step E.3 of the *evaluate* step, where the performance is evaluated from historical data to determine which scenarios are beneficial to the initiative. Thereafter, these scenarios are integrated with the evaluated

practical constraints in Step E.5 to determine the theoretical potential benefit of the initiative. During the monitor step of the methodology, a baseline and performance assessment approach is developed by adapting the recommendations made by Booysen [94]. All of this is then combined in the dynamic prioritisation of initiatives.

The integration of practical constraints into the theoretical potential quantification contributes to the accuracy of the benefit quantification methods. It is important to ensure that these methods are simplified and understood by all parties, which is addressed by considering the involved parties and their relevant skill levels as part of the practical constraints. The dynamic prioritisation uses the benefit quantification framework to ensure that interactive effects of initiatives are considered (by using Figure 17). This provides production planners with real-time recommendations of which initiatives are preferable at any given time.

Contribution 3:

*A **uniquely adopted solution** to address **personnel-related resistance** towards automated solutions at marginally profitable facilities*

The unique conditions of marginally profitable facilities (such as those in South Africa) were described in Section 1.2.2. Not only will the developed methodology be applied to such a facility, but the steps in the methodology will also be focused on these conditions. An ISO 50001-based implementation strategy was adapted in the development of the methodology to address these conditions and their constraints. Additional scope for the identification of practical constraints that a specific facility could have was incorporated into the methodology by means of Step E.4 of the evaluate step. The criteria used for comparing and prioritising initiatives for implementation also consider factors such as data availability and capital requirements.

Contribution 4:

Novel integrated model for cost-efficient steel production planning

The developed methodology uses a new approach to identify, evaluate, compare and prioritise, implement, and integrate production planning concepts to improve both energy and production cost efficiencies. This is relevant to the identified initiatives that were adapted for the methodology, and the existing solutions that were adapted and integrated in the development of the methodology. The cost model itself focuses on the integration of different production planning initiatives, different energy sources, different existing solutions, and energy and production efficiencies.

3.4. CONCLUSION

This chapter discussed the development of a new integrated cost model for steel production planning. A simplified and detailed methodology was presented and discussed in the remainder of the chapter. It was indicated how existing solutions from the literature review was used to develop the methodology. Each step was discussed in detail, with the focus of the methodology on the identification, evaluation, comparison and prioritisation, implementation, and integration of initiatives. The novel contributions were also revisited to indicate how they are addressed by the developed methodology. The next chapter presents the theoretical application of the developed methodology on a case study facility as the verification thereof.

Chapter 4: Verification

*The use of the integrated cost model for steel production planning is verified in this chapter.
This verification is achieved through the theoretical application of the methodology on a
South African steelmaking facility.*

4. VERIFICATION OF THE INTEGRATED COST MODEL

4.1. INTRODUCTION

A new integrated cost model for steel production planning was developed in the methodology of Chapter 3. The focus is now placed on applying the developed cost model to a case study facility; hereafter referred to as *Plant X* (due to confidentiality reasons). The aim of the methodology is to reduce the cost of steel production by minimising losses. The theoretical application in this chapter serves as a verification of the methodology, which is achieved by using actual data from Plant X for a full year. A practical application is conducted in Chapter 5 as validation. This provides a platform to compare the theoretically expected results with the practical results. An understanding of Plant X is required to apply the cost model.

4.2. BACKGROUND ON THE FACILITY

4.2.1. FACILITY LAYOUT

The basic layout and components of a steelmaking facility were briefly discussed in Section 1.2.4 (more detail is available in Appendix A). Plant X uses the BF-BOF production method with sinter and coke plants preceding the blast furnace to prepare the required materials. By-product gases from the blast furnace and coke plant are captured and used in the process to supplement natural gas. The gases are referred to as blast furnace gas and coke oven gas (COG). Plant X has gas holders that serve as buffers in the gas distribution network. The buffers provide a certain level of control over the gases to prevent excessive flaring. The quality of the gases are low, which makes the gases difficult to use in some processes.

The blast furnace has a production rate that can be decreased to about 60% of its maximum (the actual maximum production rate is withheld due to confidentiality reasons). A basic layout of the relevant boundary of Plant X is provided in Figure 19. After the blast furnace process, liquid iron is moved to the steelmaking facility, which consists of three BOFs. Two BOFs are typically in use, while the other one is on reline maintenance (alternating every six months). After oxygen is added to the liquid iron at the BOF, the produced liquid steel can be used by following three possible production routes, as described below:

- Production Route 1: Direct route from the BOF to the concast. This requires the steel to be refined to the exact required steel quality and temperature at the BOF. Although this was done on Plant X in the past, it is no longer considered to be an option due to outdated equipment and inexperienced personnel.

- Production Route 2: This is the most common production route at Plant X. Steel is transferred from the BOF to the ladle furnaces to be refined to the required steel quality and temperature for casting.
- Production Route 3: This route includes the vacuum degasser in the secondary metallurgy (SecMet) section, which is only required for specific steel qualities.

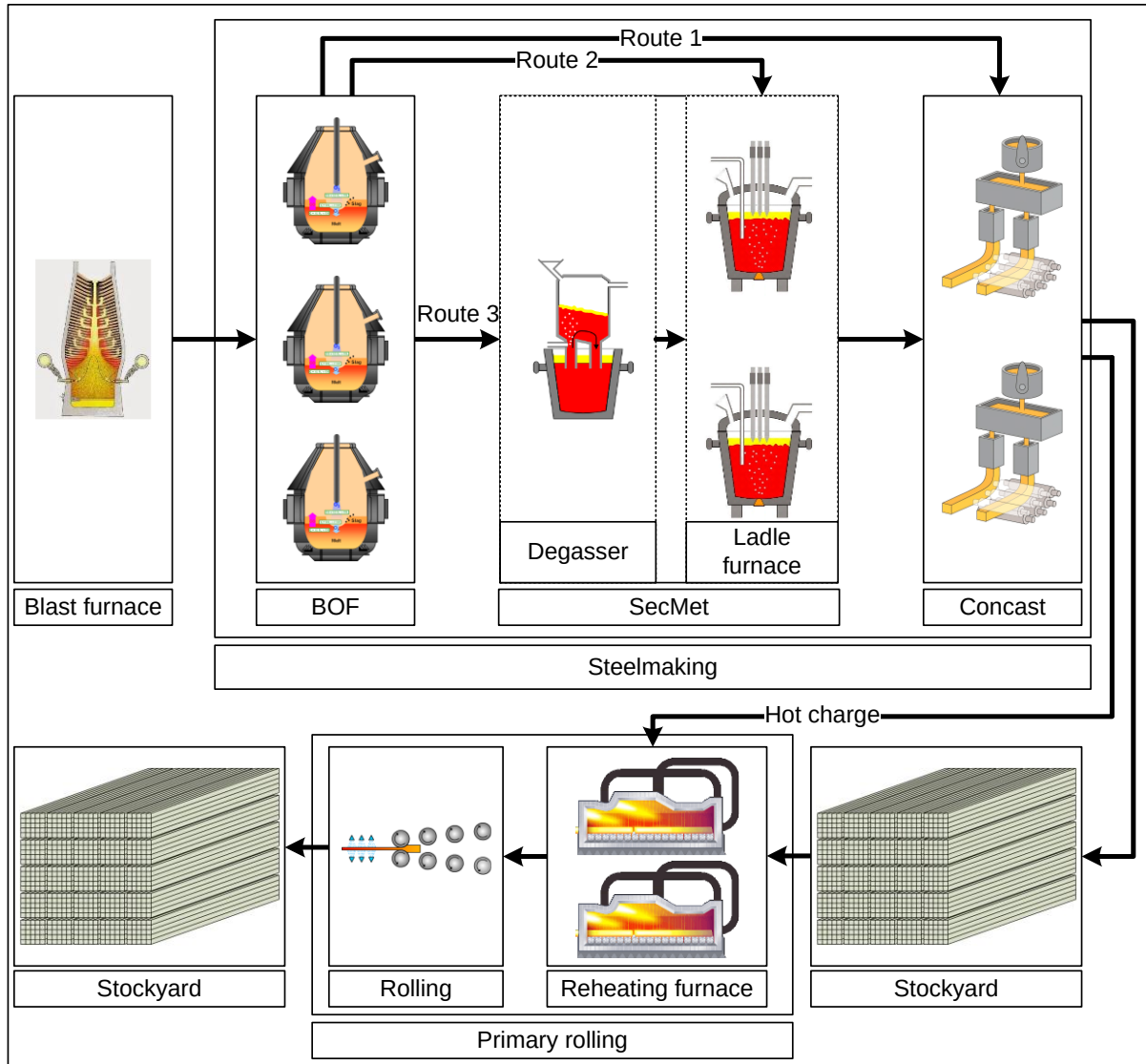


Figure 19: Basic facility layout for the steelmaking and primary rolling sections of Plant X

As indicated in Figure 19, Plant X has one degasser, which is only used occasionally (about two weeks every three months). Two ladle furnaces are used, which are high consumers of electrical energy. The facility also consists of two casters in the concast section. After steel blooms are casted, they can either be sent to a stockyard or be hot charged directly into the reheating furnace of the primary rolling mill. The primary rolling mill consists of two reheating furnaces. The number of furnaces used depends on the amount of steel that needs to be processed, which is regulated by client orders.

All infrastructure is already in place for hot charging to take place. Hot charging typically only takes place if it is observed that the next steel quality to be loaded into the reheating furnace is being casted by the concast at that instance, or for urgent orders. No special approaches are taken to increase the occurrence of these conditions. Thereafter, the heated blooms are rolled into the desired profiles (billets), and sent to another stockyard. From this stockyard, steel can either be dispatched or be refined by secondary rolling mills.

4.2.2. PRODUCTION PLANNING AT PLANT X

Plant X has two productions planners simultaneously on duty in the production planning department. They are responsible for receiving and distributing information to different entities on the facility, as indicated in Figure 20. A detailed description of the functions of these production planners are provided below.

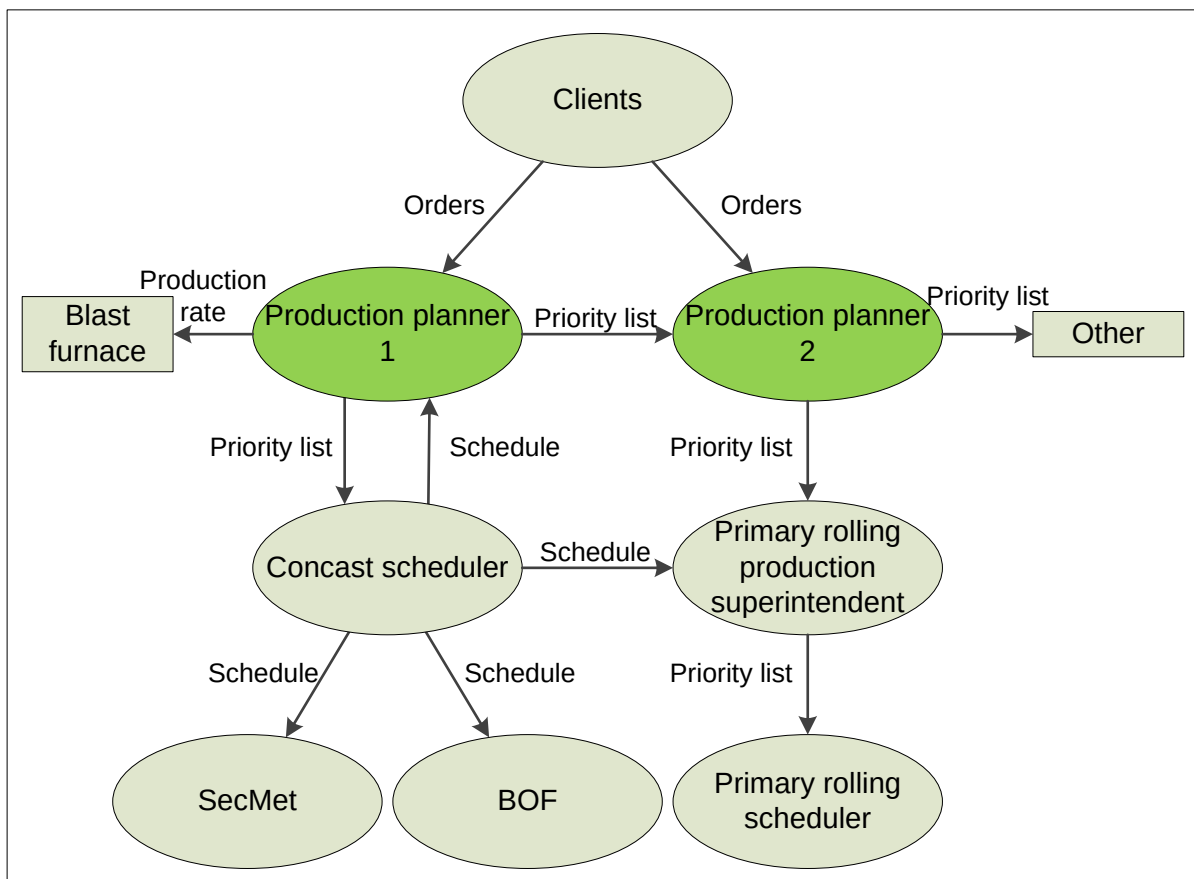


Figure 20: Production planning at Plant X

The two production planners are located at a central location, and are responsible for coordinating production based on orders from clients. The one production planner compiles a priority list for the output of the concaster, and communicates the required production rate to the blast furnace. The priority list is based on the requirements of the primary rolling mill, and typically contains information for three days in advance. The priority list is distributed to the

scheduler located at the concast, and typically changes on a daily basis. Based on the availability of equipment (due to maintenance) and liquid steel at the given time, the concast scheduler compiles a schedule for exactly which steel quality is required to be casted at what time. This schedule is available for the BOF, SecMet, primary rolling and production planning personnel.

The concast scheduler is responsible for ensuring that the liquid steel is available at the specific sections when required and according to the stated specifications. A schedule is thus compiled within the limitations of the priority list. The schedule is adapted regularly throughout the day depending on the latest available information.

Liquid steel is processed in batches of 160 tonnes (one ladle), which are transported between sections with cranes. Several delays could take place throughout the process, and the concast scheduler has to decide on mitigating actions. This concast scheduler is in regular contact with production planning, who needs to confirm any critical changes to the priority list before it can be processed.

Liquid steel is casted through a tundish at the concast, which enables the continuous casting of consecutive ladles. This is referred to as a sequence, and generally includes between six and 12 ladles depending on the orders and the specific steel qualities. Interrupting a scheduled sequence causes the loss of a tundish, which results in significant financial losses. It is thus a critical role of the concast scheduler to ensure that liquid steel is casted at the required time to prevent such losses. The typical time that a ladle spends at a processing section is one hour. After the liquid steel has been casted into blooms, it is no longer the responsibility of the concast scheduler.

The second production planner coordinates the primary and secondary rolling mills based on orders and available stock. The second production planner compiles separate priority lists for the different mills and distributes the lists to the relevant production superintendents. The concast schedule is not typically considered when compiling these priority lists. The priority lists contain information for one day at a time.

Production superintendents serve as a communication channel between the mills' schedulers and the production planner. Mill schedulers ensure that the mill furnaces are loaded with the correct amount of steel of the required steel quality, and that it is rolled into the required profile. Blooms are mostly loaded into the primary rolling mill from the stockyard, unless the production planner specifically indicates that it should be hot charged.

4.2.3. ENERGY CONSUMPTION OF PLANT X

The energy consumption of the steelmaking and primary rolling facilities of Plant X was evaluated in terms of energy cost. It was decided to use energy cost for the comparison because Plant X uses TOU billing and has varying electricity tariffs throughout the day. Energy cost will therefore play a bigger role than merely considering energy consumption. The year prior to the investigation of the facility, 2016, was used for the analysis. The energy cost distribution of these two sections is presented in Figure 21. This distribution shows that steelmaking contributes 66% of the energy cost and primary rolling 34%.

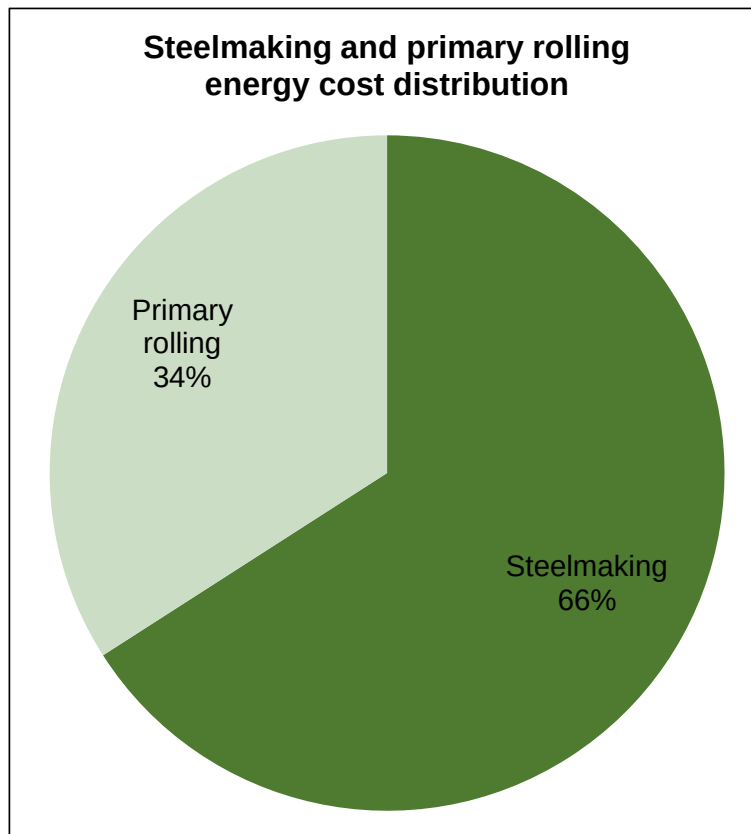


Figure 21: Comparison between steelmaking and primary rolling energy cost

The specific energy costs of different energy sources were analysed for the two plant sections to evaluate what energy sources/carriers are consumed. Energy sources were considered to include *utilities* (such as steam, argon, compressed air, nitrogen and oxygen) for this evaluation. The energy source cost distribution for 2016 for the steelmaking section is presented in Figure 22. This distribution shows that the main cost is allocated to oxygen (42%). Oxygen is consumed by the BOF during the processing of liquid iron to liquid steel. The second-largest cost is electricity (37%), which is due to the high consumption of the ladle furnaces.

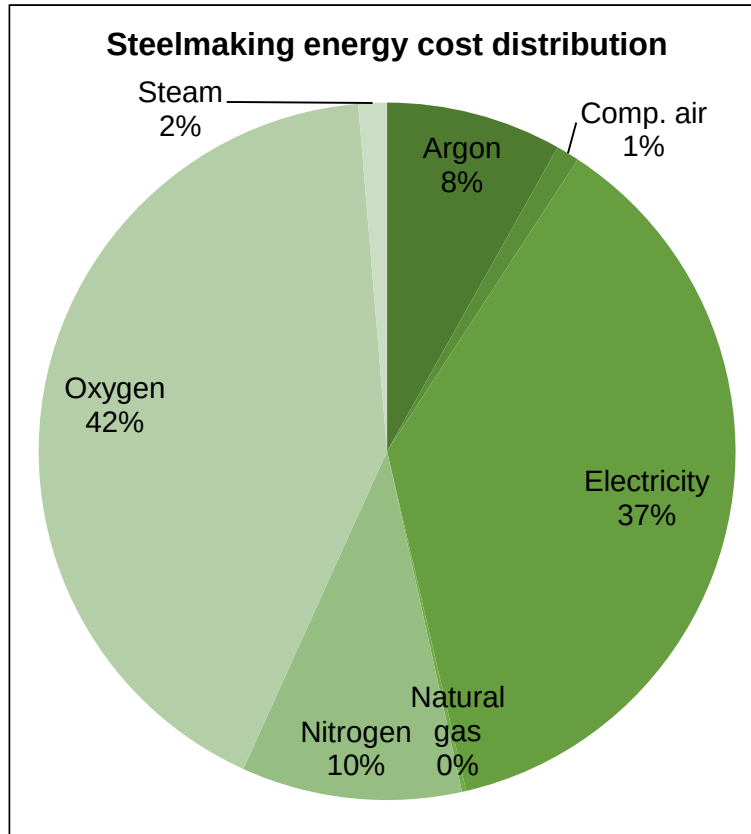


Figure 22: Steelmaking energy source cost distribution

The primary rolling mill of Plant X consumes both natural gas and COG in the reheating furnace. The COG is billed internally by the facility by allocating a cost factor to it. Figure 23 shows that during 2016 the energy cost of the primary rolling mill was made up of 45% COG, 41% natural gas, and 14% electrical energy. The larger part of the energy cost is therefore allocated to gas consumption in the reheating furnace (86%). Electrical energy is consumed by the mill motors, water pumps and other process equipment used to roll the heated steel into the required profiles. Different steel qualities have different temperature requirements, which are regulated by the gas and airflow into the furnace.

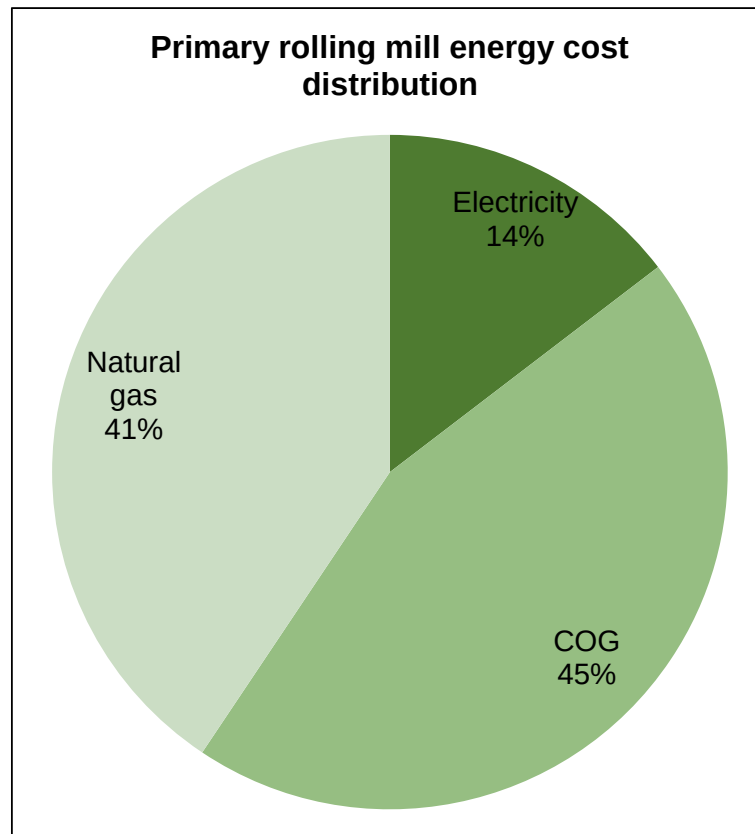


Figure 23: Primary rolling mill energy source cost distribution

4.2.4. FACILITY CHALLENGES

From discussions with personnel at Plant X and time spent investigating the operation of the different processes, several practical challenges were identified. The first limitation to production planning is the use of the BF-BOF production method, which is a continuous process with a production rate that cannot be adapted easily. The use of torpedo carts to transport liquid iron from the blast furnace to the BOF provides a slight buffer to delay the process with minimal temperature losses. There are, however, only a limited number of torpedoes available for reducing costs.

The second limitation is the age of the equipment that is being used. One example of how this affects the process negatively is that steel can no longer be processed using a Production Route 1 approach. A further example is during times when the vacuum degasser is in use, and plant personnel are not willing to consider any energy efficiency initiatives due to the complexity of refining steel with this equipment. The age of the ladle furnaces affects their ability to increase the temperature of liquid steel. Various investigations were in progress at the time to evaluate ways of improving the efficiency of the arcs.

The third major limitation experienced was resistance towards change in existing processes and the use of technological solutions. In general, Plant X was found to be a poor performing

facility (marginally profitable) compared with international facilities. This could largely be allocated to personnel resisting to cooperate and implement innovative solutions. Therefore, it was necessary to develop and implement the methodology in such a way that plant personnel would be comfortable with the approach. Most of the solutions were ISO 50001-based to address the concerns of plant personnel. This is considered to be a result of the unique conditions of marginally profitable steelmaking facilities. Capital constraints also restricted the use of automated solutions.

4.3. VERIFICATION OF THE METHODOLOGY

4.3.1. PREAMBLE

The verification of the methodology is conducted by a theoretical application thereof on Plant X. This application will verify whether it is effective to use the developed integrated cost model for steel production planning cost efficiency. The methodology will then be applied practically to the same facility in Chapter 5, which serves as validation. Most of the groundwork for the validation will be done during the verification as it is conducted on the same facility. The investigation was initiated in 2017, and information from 2016 was used for the theoretical application. The layout of the remainder of the discussion in this section is based on the methodology developed in Section 3.2 (Figure 10 and Figure 11).

4.3.2. STEP 1: GATHER PRODUCTION PLANNING INFORMATION AND IDENTIFY PRODUCTION PLANNING INITIATIVES

Gather production planning information

The basic setup of the facility was discussed in Section 4.2, with specific focus on the production planning functions in Section 4.2.2. These sections discussed the responsibilities of the two production planners. The first production planner (responsible for the steel plant) uses the following inputs when compiling a priority list:

- Stockyard content after the concast (before primary rolling);
- Blast furnace production rate;
- Steel quality (and quantity) requirements of primary rolling for the foreseeable future (about a week in advance from client orders); and
- Maintenance days of equipment.

The production planners then uses this information to compile a priority list for steelmaking, and provides the following information to the concast scheduler:

- Steel qualities required;

- Order number details of the steel qualities;
- An allocated priority number for the listed steel qualities;
- The secondary processing steps of the steel qualities;
- The required quantities of the steel qualities;
- The maximum number of ladles of the steel quality that a tundish can process; and
- The planned number of ladles to be processed.

This information is provided for three days in advance, but the list is updated daily to ensure that new inputs are considered and completed priorities are removed. When compiling this list, the production planner considers a theoretical casting plan for the two casters to ensure that sufficient liquid iron will be available to complete the orders. When compiling this list, a two-hour changeover time between casts is allocated for tundish changes. The changeover has to be considered when scheduling production to ensure that there is always one caster available to ensure that steel does not stay in the ladles for extensive periods.

The second production planner provides a priority list to the primary rolling mill using the following inputs in the process:

- New orders that were received (steel quality, profile quantity and expected completion date);
- Requirements of secondary rolling and dispatch for the foreseeable future (steel quality, profile, quantity and expected completion date for a week in advance from client orders);
- Stockyard content before the primary rolling mill; and
- Stockyard content after the primary rolling mill.

The priority list for primary rolling is then provided to production superintendents on a daily basis, which contains the following information:

- Priority number (listed in order of the earliest required date after primary rolling);
- Destination of steel after completion (secondary milling steps);
- Steel quality;
- Required profile of steel;
- Quantity of steel; and
- An indication of whether the steel should be hot charged or loaded from the stockyard.

Data for one year (2016) was used for the theoretical application of the methodology. The format of the priority lists can be used when applying the methodology on a day-to-day basis, but it is difficult to use when evaluating a longer period, such as a year. It was decided to use actual historical data for 2016 of the steel that was processed by Plant X. This data was

processed to be linked to 366 virtual schedules, which are assumed to have been distributed for each day of the year. The actual time of day that processing took place was stripped from these schedules, leaving only the information available in the priority lists.

This approach made it possible to have data for a long period of time in a format that is practical for processing without any unnecessary information or information that would not have been available at the time. Therefore, the theoretical performance and potential benefits of the production planning functions can be evaluated using this data. This is discussed in the remainder of this section.

Identify production planning initiatives for the facility

The integrated cost model suggests that production planning initiatives be identified from a literature review and discussions with plant personnel. A literature review to identify such initiatives was conducted in Section 2.4, from which five potential initiatives were identified. The initiatives were listed and summarised in Table 12 (Section 0) as follows:

- Hot charging of the primary rolling mill furnace;
- Ladle furnace load shifting;
- Ladle and crane time loss reduction;
- Primary rolling mill apportionment model; and
- Primary rolling mill load shifting.

4.3.3. STEP 2: EVALUATE PRODUCTION PLANNING INITIATIVES

Overview

This step in the methodology consists of five separate steps, which evaluates each initiative separately. Each step has four categories in which an initiative must be placed. These categories will also be discussed in this sub-section.

Step E.1: Determine the status of the initiative on the facility

Overview

A summary of the status of each initiative at Plant X is provided in Table 15, followed by a more detailed discussion for each initiative.

Table 15: Status overview for identified initiatives

Initiative	Status
Hot charging of the primary rolling mill furnace	Implemented, but not effective
Ladle furnace load shifting	Not previously considered

Initiative	Status
Ladle and crane time loss reduction	Not previously considered
Primary rolling mill apportionment model	Not previously considered
Primary rolling mill load shifting	Previous unsuccessful attempt

Hot charging of the primary rolling mill furnace

As described in Section 4.2.1, all infrastructure, such as cranes and conveyer systems, is already available for hot charging to take place. Hot charging currently takes place if conditions allow it. It was, however, found that there is not a large drive for hot charging on Plant X, even though all parties are aware of its production benefit. Plant X has a targeted hot charging rate of 40%, but the hot charging rate for 2016 was only 27%. According to literature, most Japanese steelmaking facilities have a hot charging rate of 100%, highlighting the significant scope that exists to improve the current hot charging of Plant X [36]. The initiative is categorised as *implemented, but not effective* in Table 15.

Ladle furnace load shifting

The initial idea with electrical load shifting on the ladle furnaces was to use Production Route 1 during peak times, and to resultantly eliminate the ladle furnaces completely. From discussions with plant personnel, this was, however, found to not be practically possible due to the age of equipment. Some evaluations to quantify the cost of producing steel involved evaluating the electrical energy required to produce different steel qualities. These evaluations indicated that there was variation in the electrical energy intensity to process different steel qualities, and the investigation was adapted accordingly. Such load shifting has, however, *not been considered previously*.

Ladle and crane time loss reduction

An investigation into how the scheduling of ladles and cranes for production works indicated that there was no regulation of this process. The only form of control was the selection of which ladle furnace to use depending on the caster that the specific steel was scheduled for. It was concluded that this initiative *has not been considered previously*.

Primary rolling mill apportionment model

Upon investigating the status of the apportioning of different steel qualities with similar specification, it was found that steel qualities were currently loaded into the furnace per cast as coordinated with the orders. There were thus already several blooms grouped together, all of which was the exact same size and steel quality. However, no attempt was made to coordinate casts with one another based on their specifications. Orders with the same profiles

were grouped together to reduce the number of changes to the mill setup. The effect on furnace gas consumption was, however, not taken into consideration. The initiative *has thus not been considered previously*.

Primary rolling mill load shifting

From the discussions with plant personnel it was found that a similar initiative has previously been considered. Plant personnel mentioned that there is a surplus COG available, and suggested that the additional COG be used to increase the temperature of the furnace during peak electricity tariff periods. The personnel suggested that this would soften the blooms slightly, causing less strain on the rolling mills, which would resultantly reduce the power consumption during these times. It was decided to exclude this as part of the investigation as plant personnel did not want to revisit this idea. There was thus a *previous unsuccessful attempt* for this initiative.

Step E.2: Collect the required historical data

The next step in evaluating the initiatives is determining what historical data is available for analysis. Table 16 lists the ideally required data used to evaluate its availability and resolution.

Table 16: Required historical data for identified initiatives

Initiative	Required historical data	Availability
Hot charging of the primary rolling mill furnace	Hot charging percentage (if applicable)	Daily
	Steel qualities rolled by mill	Per cast
	Steel profiles rolled by mill	Per cast
	Steel qualities casted by the concast	Per cast
	Steel orders, with required completion dates	Per cast
	Steel tonnages processed	Per cast
	Furnace gas consumption	Daily totals
	Steel input temperature	Limited availability
	Steel output temperature	Limited availability
	Furnace temperatures	Limited availability
Ladle furnace load shifting	Steel quality processed	Per cast
	Input temperature	Per cast
	Output temperature	Per cast
	Duration of heating cycle	Per cast
	Energy consumption of heating cycle	Per cast
	Production route followed	Per cast
	Electricity tariffs	Available
	Which ladle furnace was used	Per cast

Initiative	Required historical data	Availability
Ladle and crane time loss	Time at which steel is required at caster	Per cast
	Which crane was used	Not available
	Duration of movement	Can be calculated
	How often the crane is used	Not available
	Which ladle was used	Not available
	Duration of heating cycle	Per cast
	How often the ladle is used	Not available
Primary rolling mill apportionment model	Steel quality processed	Per cast
	Steel profile rolled by mill	Per cast
	Steel input temperature	Limited availability
	Steel output temperature	Limited availability
	Steel tonnages processed	Per cast
	Furnace gas consumption	Daily totals
	Furnace temperatures	Limited availability
Primary rolling mill load shifting	Steel quality processed	Per cast
	Steel profile processed	Per cast
	Power consumption profile of mill motors	Half-hourly
	Electricity tariffs	Available

From this summary, the data availability of each initiative on the facility was categorised as described in the methodology, with a summary provided in Table 17.

Table 17: Data availability overview for identified initiatives

Initiative	Data availability
Hot charging of the primary rolling mill furnace	All desired data is sustainably available
Ladle furnace load shifting	All desired data is sustainably available
Ladle and crane time loss reduction	Selective data is available
Primary rolling mill apportionment model	Selective data is available
Primary rolling mill load shifting	All desired data is sustainably available

Step E.3: Evaluate the performance from historical data

Overview

The historical performance of each initiative on the facility was evaluated and categorised as described in the methodology. A detailed evaluation of each initiative is provided in Appendix B, with a basic summary of the findings shown in Table 18.

Table 18: Summary of theoretical evaluation of historical performance (summary of Appendix B)

Initiative	Findings	Reference
Hot charging of the primary rolling mill furnace (Appendix B.2)	Increased hot charging reduces the energy intensity of the primary rolling mill furnace.	Figure 63
	Theoretical daily cost benefits were calculated for hot charging ranges.	Table 32
	Increased hot charging has production and gas consumption benefits.	Figure 65
Ladle furnace load shifting (Appendix B.3)	Different steel qualities have varying energy consumption at the ladle furnaces.	Figure 67
	Ladle Furnace 2 consumes 1.2 MWh/heat more than Ladle Furnace 1.	Figure 68
	The maximum variation between highest and lowest energy consuming steel qualities was calculated as 1.9 MWh/heat for Production Route 2 and 5.7 MWh/heat for Production Route 3.	Figure 69
	The maximum theoretical cost benefit per heating cycle was calculated as R4 500 for Production Route 2 and R13 200 for Production Route 3 steel qualities.	Figure 70
Ladle and crane time loss (Appendix B.4)	Transfer time from the BOF to Ladle Furnace 2 is two minutes less than that of the BOF to Ladle Furnace 1.	Figure 71
	Transfer time from Ladle Furnace 2 to the concast is approximately 1 minute less than from Ladle Furnace 1.	Figure 72
	The average time for a ladle to be casted is 50 minutes.	Figure 73
	The facility needs to operate at full capacity to quantify the increased production as a cost benefit.	n/a
	Historical data indicates that Plant X never operated at maximum capacity during 2016.	n/a
Primary rolling mill apportionment model (Appendix B.5)	There is a variation in the gas flow (m ³ /h) required to maintain the required average temperature (°C) of different steel qualities.	Figure 74
	This variation is not consistent enough to be considered as potential to reduce cost.	Figure 75; Figure 76
Primary rolling mill load shifting (Appendix B.6)	There is a 2.2 MW variation between the highest and lowest power consuming steel quality/profile combinations.	Figure 77
	Theoretical maximum potential cost benefit of R24 500 per day.	Figure 78

A summary of the historical performance categories for each initiative is provided in Table 19.

Table 19: Historical performance overview for identified initiatives

Initiative	Historical performance
Hot charging of the primary rolling mill furnace	Sufficient variation exists between scenarios
Ladle furnace load shifting	Sufficient variation exists between scenarios
Ladle and crane time loss reduction	Limited variation between scenarios
Primary rolling mill apportionment model	No variation between scenarios
Primary rolling mill load shifting	Possible variation between scenarios

Step E.4: Evaluate any practical constraints for the initiative

Overview

The practical constraints of the identified initiatives were evaluated for Plant X and categorised as described in the methodology. A summary of the practical constraints categorisation of each initiative is provided in Table 20, followed by a more detailed discussion for each initiative. Practical constraints were determined based on an evaluation of the ideal conditions compared with the actual conditions, and discussions with relevant personnel. These conditions should also be considered when implementing initiatives, as mitigating these constraints will be the main contributor towards achieving the potential benefits.

Table 20: Practical constraints overview for identified initiatives

Initiative	Practical constraints
Hot charging of the primary rolling mill furnace	Little to no practical constraints exist
Ladle furnace load shifting	Resistance exists
Ladle and crane time loss reduction	Resistance exists
Primary rolling mill apportionment model	Practical constraints cannot be mitigated
Primary rolling mill load shifting	Resistance exists

Hot charging of the primary rolling mill furnace

As indicated in Step E.1, hot charging of the primary rolling mill furnace already takes place at Plant X. All of the required infrastructure is in place, and no capital is required to increase this performance. From discussions with plant personnel it was found that all parties are positive towards increasing hot charging, and that they agree that it entails benefits. It was, however, indicated in Step E.1 that hot charging is not currently conducted as effectively as targeted.

This was confirmed by the evaluation of historical data in Step E.3 (and Appendix B), and the reasons behind it had to be investigated.

It was found that on Plant X, the production planning of the steelmaking and primary rolling facilities are mainly conducted separately, and only compared afterwards. This was found to cause the respective production planners and schedulers to not always identify opportunities, or to realise it is too late to utilise the opportunities. Another issue is that it is physically labour intensive to change the profile that is rolled by the mill, and that plant personnel are reluctant to make regular changes. This leads to orders of the same profiles being grouped together regardless of whether these orders are being casted (and can be hot charged) or being loaded from the stockyard.

Ladle furnace load shifting

In terms of the infrastructure required to perform electrical load shifting on the ladle furnaces, no capital is required. The concept of moving steel qualities around within the same schedule is possible, and no physical changes are required at Plant X. There are, however, some practical constraints in terms of utilising the maximum theoretical benefit. These constraints entails possible risks for Plant X, causing some resistance towards the initiative from plant personnel.

The first practical constraint is that it is more cost-effective to cast longer sequences of the same steel quality at the concast. The cost of relining a tundish between sequences was said to be almost R80 000, which is higher than the maximum theoretical benefit of the initiative. Additionally, changing a tundish (and resultantly a sequence) was reported to take up to two hours, inducing a large time delay in the production process. In terms of ladle furnace load shifting, this implies that steel qualities cannot be produced during the most convenient times throughout the day, as steel has to be produced consecutively depending on the required sequence length.

Due to the use of the BF-BOF approach on the facility, production takes place continuously. Production planners are expected to adapt operations depending on the blast furnace production rate and available liquid iron level at the time. The product planner takes this effect into account when compiling the priority list, but it has to be monitored by the concast scheduler in real time. The scheduler is always aware of the latest liquid iron quantity in transit (moving between operations and currently being processed). The scheduler is expected to maintain this level between 100 tonnes and 1 000 tonnes at any instance. This ensures that there is enough steel available for processing, but not so much that the steel cannot be processed in time.

The last practical constraint to be considered is the effect that ladle furnace scheduling and hot charging will have on one another. Due to the more time sensitive priority list of the primary rolling mill, it is expected from the steelmaking facility to produce any urgent order as soon as possible. If any sudden changes occur in the production plans, this would lead to a compromise at the steelmaking facility, and a loss of opportunity to do load shifting on the ladle furnaces. One of the schedules will be expected to be adapted based on the requirements of the other. This study suggests that energy cost be included in this decision-making process.

Ladle and crane time loss reduction

Although all physical infrastructure was in place for Ladle Furnace 2 to be used more than Ladle Furnace 1, there were concerns that Ladle Furnace 2 would be overused, as well as concerns regarding the effect that its overuse would have on its performance. Ladle Furnace 2 was already considered to be less energy efficient than Ladle Furnace 1, highlighting the importance of regular and proper maintenance. It was concluded that if Plant X is operating at maximum production, it would become an option to implement this initiative, but that plant personnel would prefer to have a good balance between using the different ladle furnaces.

Primary rolling mill apportionment model

The evaluation of the historical data for this initiative already showed that there is not a sufficiently clear pattern in the isolated scenarios to utilise any potential benefit. It was confirmed by plant personnel that most of the blooms loaded into the primary mill furnace are of the same size, and that the most variation is in the steel qualities. Possible reasons for the lack of a pattern in the data scenarios that were analysed were indicated as:

- The furnace being hot charged in some of the scenarios;
- Different furnaces being used in the scenarios;
- Different gases being consumed; or
- COG quality not being consistent.

These practical constraints can therefore not be mitigated.

Primary rolling mill load shifting

The practical constraints for primary rolling mill load shifting are similar to those of ladle furnace load shifting. It is also preferred by plant personnel to complete a sequence/order before proceeding with the next one. In this case, however, there are not severe cost effects when *breaking* a sequence, but it could have negative effects on the furnace stability, and it is also labour (and time) intensive to change between different profiles at the mills. Therefore,

plant personnel prefer to minimise profile changes throughout the day. Another effect is that there is limited variations in the steel quality/profile combinations processed throughout the day. This limitation can influence the cost benefit.

The production outputs of the primary rolling mill are mainly dependent on the orders that were placed. Unlike the steelmaking priority list that is provided for three days in advance, the primary rolling mill priority list only provides the outputs for one day. All the steel qualities and profiles on the priority list have to be completed within one day, and limited flexibility exists. This is accompanied by the content and management of the stockyard. It is time-consuming to move blooms around the stockyard, and impulsive changes to the schedule cannot be made without prior notice to the crane operators.

Lastly, none of the involved parties were aware of the TOU tariffs or periods during the discussions. This was never considered a factor when performing production planning, and it was considered as a new concept by the involved parties. Apart from the practical constraints discussed above, there was resistance from plant personnel to attempt the implementation of such an initiative. All infrastructure is, however, already in place, and it is possible to gain benefits from such an initiative.

Step E.5: Determine the theoretical potential benefit

Overview

The potential benefit of each initiative on the facility was evaluated and categorised as described in the methodology. A summary of the potential benefit categorisation of each initiative is provided in Table 21, followed by a more detailed discussion for each initiative. The maximum theoretical benefits of initiatives were calculated by using the 2016 data set, and will be discussed for each initiative.

Table 21: Potential benefit overview for identified initiatives

Initiative	Potential benefit
Hot charging of the primary rolling mill furnace	Benefits are achieved when conditions allow them
Ladle furnace load shifting	Potential benefits exist to be utilised
Ladle and crane time loss reduction	Limited potential exists
Primary rolling mill apportionment model	No potential exists
Primary rolling mill load shifting	Potential benefits exist to be utilised

Hot charging of the primary rolling mill furnace

From the evaluation of historical data and practical constraints, it was found that it would be possible to increase the current hot charging rate. The 2016 data set was used, and similarities between the casting and primary rolling priority lists were flagged. From this evaluation it was determined that the potential hot charging rate during 2016 was 46%, which was higher than the achieved rate of 27% and the targeted rate of 40%. By using the established regression lines (Appendix B) and applying them to each day of 2016 for the relevant production and possible hot charging rate, the potential benefit was calculated as R8.7 million.

The daily theoretical cost benefit for this initiative is presented in Figure 24. From this figure and the potential benefit calculation it is established that there is potential that can be utilised. Due to the actual achieved hot charging rate of 27%, this initiative is classified as *benefits are achieved when conditions allow them*.

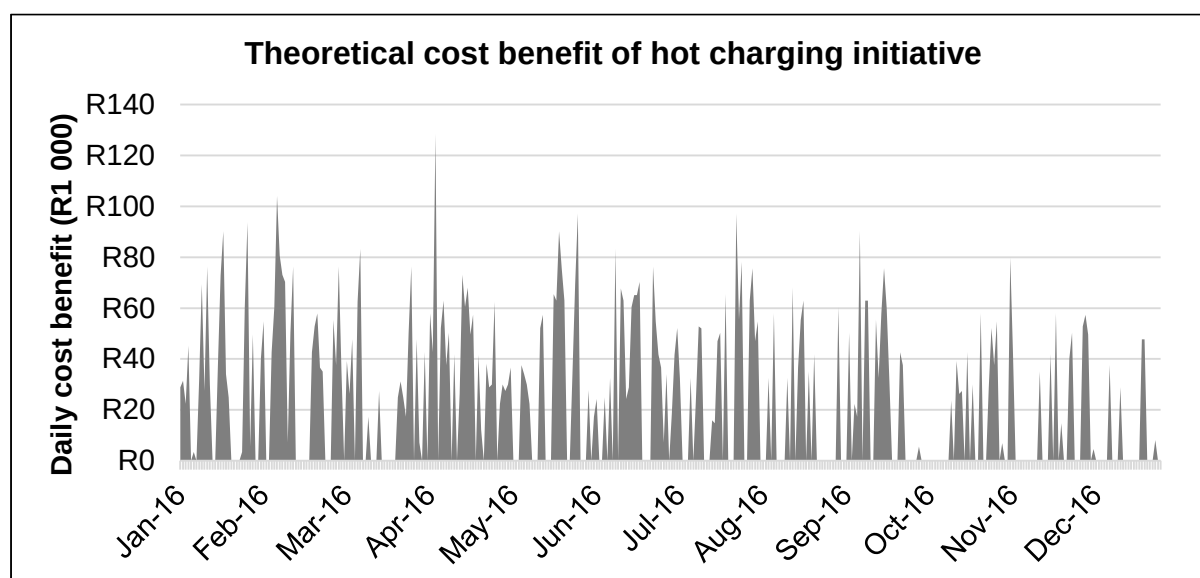


Figure 24: Theoretical cost benefit of the increased hot charging initiative for 2016

Ladle furnace load shifting

The evaluation of historical data and practical constraints for ladle furnace load shifting indicated that it would be possible to achieve benefits from this initiative. The 2016 data was used to calculate the potential benefit at Plant X. This was done by comparing the best- and worst-case allocation of steel qualities into the TOU tariff periods. The five highest and lowest energy consuming steel qualities were identified for each day, and the ideal allocation was compared with the least ideal allocation. The maximum theoretical potential benefit for the initiative on Plant X for 2016 was calculated as R3.3 million.

The daily theoretical cost benefit for this initiative is presented in Figure 25. The figure shows that the potential benefit of this initiative is larger during the three winter months when TOU tariffs are higher. It is established from this representation and the calculated theoretical cost benefit that *potential benefits do exist for this initiative to be utilised*.

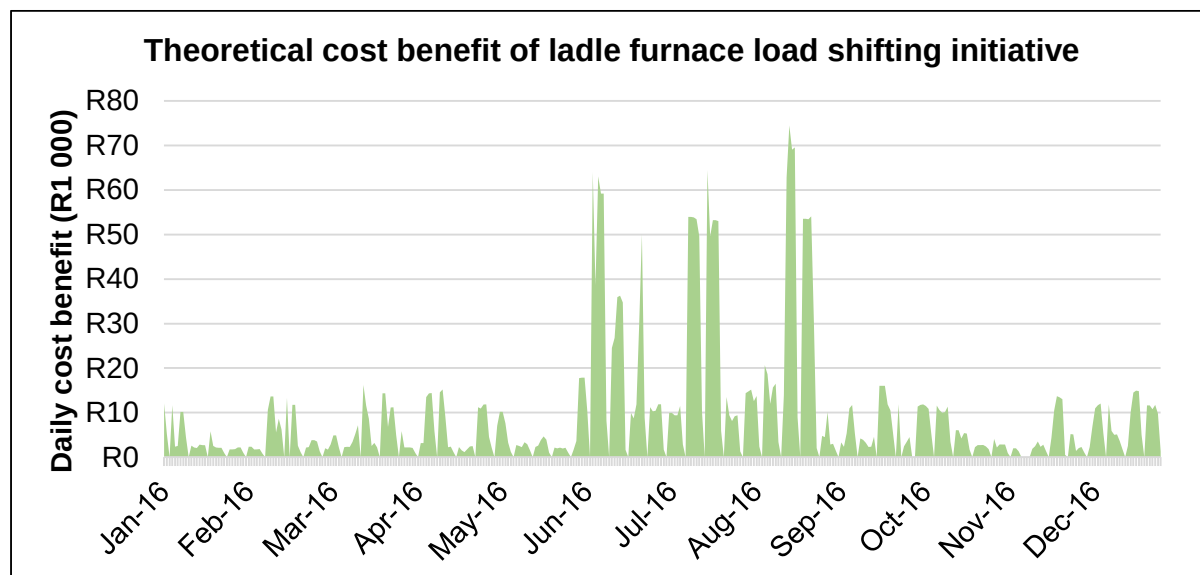


Figure 25: Theoretical cost benefit of the ladle furnace load shifting initiative for 2016

Ladle and crane time loss reduction

The evaluation of historical data indicated that there was some variation in the transfer times when using different ladle furnaces for production. The lack of sufficient data caused the investigation to be limited, and it was indicated by the practical constraints that plant personnel were opposed to such an initiative. It was, however, established that the benefit could be utilised if the plant is operating at maximum production, but that it would not have an effect at any other time. The analysis of 2016 data indicated that Plant X did not operate at maximum production once, and that there was no theoretical potential benefit to be utilised. There was therefore *limited potential* to gain benefits from this initiative in future at Plant X.

Primary rolling mill apportionment model

From the evaluation of historical data and the practical constraints it was determined that *no potential benefit could be obtained* from this initiative at Plant X.

Primary rolling mill load shifting

The 2016 data set was used to calculate the maximum theoretical potential benefit for the primary rolling mill load shifting at Plant X. The analysis was conducted in a similar manner as that of ladle furnace load shifting, and the five highest and lowest energy consuming combinations were identified for each day. The worst- and best-case scenarios were

compared, and the maximum theoretical potential benefit for the initiative at Plant X during 2016 was calculated as R400 000. The theoretical daily cost benefit for this initiative is presented in Figure 26. From this figure it is also seen that the potential benefit is larger during the winter months, which is as expected. It is established that *potential benefits do exist* for this initiative to be utilised.

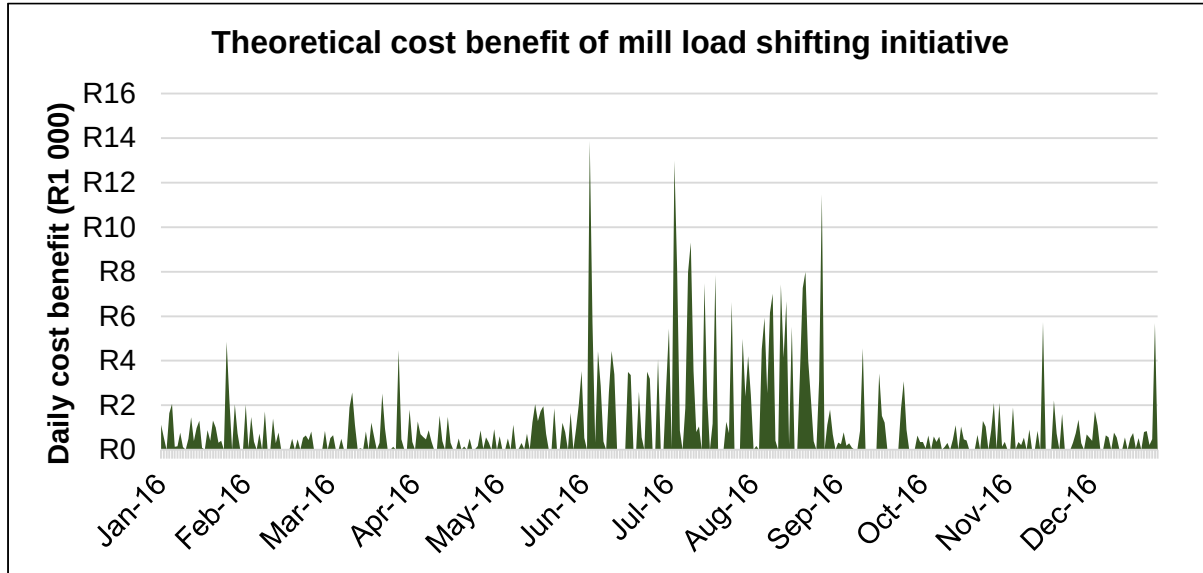


Figure 26: Theoretical cost benefit of the primary rolling mill load shifting initiative for 2016

4.3.4. STEP 3: COMPARE AND PRIORITISE PRODUCTION PLANNING INITIATIVES

Compare evaluated initiatives

By using the classification of the initiatives discussed in the previous section and allocating the relevant values for each initiative as discussed in the methodology (Table 13), the initiative rankings are calculated as indicated in Table 22 (by using Equation 6). The comparison of the initiatives for Plant X indicates that ladle furnace load shifting is the highest ranked initiative, followed by the hot charging initiative, and then the primary rolling mill load shifting initiative. It was decided that the apportionment model would be removed from further discussions as it was not considered as feasible at Plant X.

Table 22: Comparison of evaluated initiatives

Step	Description	Hot charging of the primary rolling mill furnace	Ladle furnace load shifting	Ladle and crane time loss reduction	Primary rolling mill apportionment model	Primary rolling mill load shifting
E.1	Status	0	2	2	2	-1
E.2	Data availability	2	2	-1	-1	2
E.3	Historical performance	2	2	-1	-2	0
E.4	Practical constraints	2	0	0	-2	0
E.5	Potential benefit	0	2	-1	-2	2
Initiative ranking		8	10	-2	-9	5

Prioritise production planning initiatives

Based on the comparison of initiatives in the previous step, the static prioritisation of implementing initiatives at Plant X was conducted. The order in which the implementation steps (based on ISO 50001) will be discussed will be adapted from the previous order of discussion for initiatives. The priority list for implementing initiatives is as follows:

- i. Ladle furnace load shifting
- ii. Hot charging of the primary rolling mill furnace
- iii. Primary rolling mill load shifting
- iv. Ladle and crane time loss reduction

4.3.5. STEP 4: IMPLEMENT PRODUCTION PLANNING INITIATIVES (ISO 50001)

Adapt production planning initiative

Overview

As discussed during the development of the methodology, the *adapt-implement-monitor-revise* steps in the approach are based on the PDCA approach of ISO 50001. The use of the *adapt* step is therefore verified by its association with the *plan* step of ISO 50001. Due to the theoretical application nature of the verification of the methodology, the initiatives are not implemented practically. The implementation for these four steps are, however, discussed at the hand of their relevant ISO 50001 steps with suggestions on how they can be conducted

practically. This step plans for the implementation of each of the initiatives by adapting them from the previous applications considered in literature.

Ladle furnace load shifting

This initiative was identified from literature in Section 2.4.3 for an EAF, where delays could be induced between casts to adapt to varying electricity tariffs. The initiative was, however, adapted for Plant X to be applicable to ladle furnaces in the BF-BOF production method by utilising the differences in energy intensities of different steel qualities. The difference from literature is that the energy consumption cannot be reduced to zero during peak times as production cannot be delayed as easily. The maximum potential benefit is reduced to the difference between the highest and lowest energy consuming steel qualities scheduled for the day.

An advantage of this adaption is that it introduces a method for steelmaking facilities to utilise the benefits of varying electricity tariffs without compromising on production. This adaption addresses the practical concerns raised during Step E.4 as it will prevent unscheduled tundish changes if production takes place continuously. The scheduler will also be able to maintain the liquid steel level within the required limits. It is expected that the resistance from plant personnel will be addressed by using an ISO 50001-based implementation strategy with additional tools that can be used to assist with decision-making.

Hot charging of the primary rolling mill furnace

The main differences between the hot charging initiatives discussed in the literature review of Section 2.4.2 and its application on Plant X is the resistance from personnel to use automated solutions. Most of the cases evaluated in literature used automated software solutions to schedule production, and resultantly optimise hot charging. This has to be adapted for Plant X; it is also suggested to use an ISO 50001-based implementation strategy with assistive tools to achieve this. It is suggested to rather flag possible opportunities at Plant X for production planners and to provide feedback on missed opportunities.

Primary rolling mill load shifting

Primary rolling mill load shifting was identified by combining different concepts from the literature discussed in Section 2.4.6. The main difference is that load shifting initiatives on other facilities often focus on service delivery equipment, while this initiative focuses on load shifting production outputs. The resistance from personnel was mainly experienced due to their concerns regarding production losses. This was addressed by analysing the energy intensity of different steel quality/profile combinations. It is suggested to use the same

approach as with ladle furnace load shifting by scheduling lower energy consuming combinations in peak time, rather than delaying production.

Another concern from personnel regarding this initiative is that they were not convinced of the possible benefit of such an initiative based on the discussion thereof. Special attention will have to be given to training personnel and informing them about the possible benefit that the initiative entails. It might be required to make more regular profile changes, which is a labour- and time-intensive process. Personnel will have to be aware of the possible benefits to ensure that they are cooperating to perform the necessary practical steps to utilise the benefits.

Ladle and crane time loss reduction

The ladle and crane time loss reduction initiative identified from literature in Section 2.4.4 suggested the use of software to reduce time losses. The first adaption to be made is to rather flag opportunities with an ISO 50001-based implementation strategy than to automate the system. This will mitigate the concerns from personnel regarding the use of automated solutions to perform production planning. Another compromise that will be required is to rather focus on the ladle furnace selection due to a lack of information and control over the crane and ladle selection. The initiative will focus on an increased utilisation of Ladle Furnace 2 at Plant X, rather than focusing on the ladle and crane time loss reduction.

Implement production planning initiative

Overview

The use of the *implement* step in the methodology is verified by basing it on the *do* step of ISO 50001. It was discussed during the development of the methodology that this step consists of four sub-steps (Figure 16 in Section 3.2.5). These sub-steps are aimed at developing and implementing the solutions for each identified initiative by addressing the practical constraints and required adaptations from the applications in literature. The sub-steps are discussed from a theoretical point of view for each initiative.

Ladle furnace load shifting

Step I.1: Compile and simplify assistive tools for production planning to use

Assistive tools to allow schedulers and production planners to utilise potential benefits have to be developed. For this initiative, the following should be used:

- Reference sheets indicating the steel qualities that are safe for peak time production, based on the energy intensity of steel qualities in Appendix D;

- A software-based interface that schedulers can use to adapt planned schedules to compare scenarios and instantaneously evaluate the cost benefits of suggested changes;
- Modifications to the priority list distributed by the production planner to indicate TOU periods and the energy intensity of different steel qualities; and
- TOU clocks in the control room for schedulers to easily see what the current and next TOU tariff periods are.

Step I.2: Create awareness by highlighting and discussing benefits

After creating these tools, schedulers and production planners have to be trained on how to use the tools. Additionally, other personnel that could be influenced also have to be trained and informed about the benefits and planned implementation on Plant X. Training can either take place in the form of presentations or technical discussions using information sheets. The following is suggested for inclusion in the training of personnel for this initiative:

- An explanation of the frequency graphs (Figure 67 and Figure 68), and how they were used to determine which steel qualities are more energy intensive;
- An explanation of how the potential benefits were determined (Figure 69 and Figure 70);
- An indication of the maximum theoretical potential benefit that can be achieved; and
- General indications of how to utilise opportunities, such as scheduling maintenance in peak times, and moving more energy intensive steel qualities to evenings and weekends.

Step I.3: Create an assistive system to flag opportunities

To maintain awareness and ensure that the initiative is implemented actively, it is important to flag opportunities based on the priority lists compiled by production planners. This will ensure that schedulers are aware of the potential benefit for the day. The following can be included in the flagging report for this initiative:

- An indication of the highest and lowest energy consuming steel qualities on the latest priority list; and
- An indication of the potential benefit of the best and worst-case scenarios for the latest priority list (Figure 70).

Step I.4: Implement the initiative

The implementation takes place by introducing all the above-mentioned tools to the different parties. Resistance from personnel and poor communication are problems at Plant X, and it is important to fill this gap by serving as a communication channel between different entities. It is critical to ensure that the developed tools are used, and that potential benefits are utilised.

Hot charging of the primary rolling mill furnace

Step I.1: Compile and simplify assistive tools for production planning to use

The suggested assistive tools for use at Plant X to increase hot charging is the following:

- Modifications to the priority list to indicate the expected completion time and date of orders (to enable schedulers to make informed suggestions to production planners);
- Schedulers and production superintendents should also receive the priority list for the steelmaking facility to understand their planned outputs; and
- A software-driven interface where the planned number of casts to be processed and to be hot charged can be given as inputs and an estimated cost benefit given as output.

Step I.2: Create awareness by highlighting and discussing benefits

The following should be used for the awareness creation training to personnel at Plant X regarding increased hot charging:

- Indications of the effect on energy consumption per tonne production for different hot charging rates (Figure 63 in Appendix B.2);
- An indication of the gas cost reduction for increased hot charging rates (Table 32 in Appendix B.2);
- An indication of the effect that increased hot charging has on the energy intensity of the mill furnace (Figure 64 in Appendix B.2); and
- The potential production and energy increases of reaching the hot charging target of 40% (Figure 65 in Appendix B.2).

Step I.3: Create an assistive system to flag opportunities

The following should be included in the flagging system for increased hot charging at Plant X:

- Steel qualities that are on the latest steelmaking and primary rolling mill priority lists;
- The potential benefit of hot charging all the correlating steel qualities on the latest priority lists;
- An indication of the percentage of the correlating steel qualities that are already scheduled for hot charging; and
- An indication of the possible missed opportunities if only the scheduled steel qualities are hot charged.

Step I.4: Implement the initiative

Additional methods for implementing the increased hot charging initiative at Plant X are:

- Reducing the stockyard before the primary rolling mill (hot charge all steel possible); and
- Loading cold casts between hot casts to ensure that orders from the stockyard are processed, but that the possible hot charging opportunities are utilised.

Primary rolling mill load shifting

Step I.1: Compile and simplify assistive tools for production planning to use

The assistive tools for mill load shifting at Plant X are similar to those of ladle furnace load shifting, as listed below:

- Reference sheets indicating the steel qualities/profile combinations that are most beneficial to peak time production based on the energy intensities of such combinations in Appendix G;
- A software-based interface where schedulers can compare scenarios and evaluate the potential cost benefits;
- Modifications to the priority list to indicate the energy intensity of different combinations and during which periods production is suggested; and
- TOU clocks in the control room to clearly show schedulers what the current and next TOU tariff periods are.

Step I.2: Create awareness by highlighting and discussing benefits

The awareness creation training for this initiative is similar to that of ladle furnace load shifting, and should include the following:

- An explanation of the energy intensity frequency graphs (Figure 77 in Appendix B.6), and how they were used to determine which combinations are more energy intensive;
- An explanation of how potential benefits were determined (Figure 78 in Appendix B.6);
- An indication of the maximum theoretical potential benefit that can be achieved; and
- General indications of how to utilise opportunities, such as scheduling maintenance in peak times and moving more energy intensive combinations to evenings and weekends.

Step I.3: Create an assistive system to flag opportunities

As with ladle furnace load shifting, the following should be included in the flagging report:

- An indication of the highest and lowest energy consuming combinations on the latest priority list; and
- An indication of the potential benefit of the best- and worst-case scenarios for the latest priority list (Figure 78 in Appendix B.6).

Step I.4: Implement the initiative

The implementation of the initiative will be based on the introduction of the above-mentioned tools to plant personnel.

Ladle and crane time loss reduction

Step I.1: Compile and simplify assistive tools for production planning to use

For the ladle and crane time loss reduction initiative at Plant X it was determined that there are potential benefits, but that the benefits are only relevant when the facility is operating at maximum production. The assistive tools should monitor the blast furnace production rate, and if it reaches maximum capacity, provide a notification to schedulers indicating the following:

- Recommendations regarding which ladle furnace to use, giving preference to Ladle Furnace 2 whenever it is available;
- Provide the scheduler with an estimated completion time of a ladle using different ladle furnaces; and
- Indicate the potential cost benefit of using different ladle furnaces.

Step I.2: Create awareness by highlighting and discussing benefits

Awareness regarding the benefits of the increased use of Ladle Furnace 2 during maximum production can be achieved by including the frequency plots of Step E.3 (Figure 72 and Figure 73) in training sessions.

Step I.3: Create an assistive system to flag opportunities

The flagging system will be incorporated in the assistive tools for schedulers discussed in Step I.1. This system should provide a notification to the scheduler to increase the utilisation of Ladle Furnace 2 if the blast furnace reaches maximum production.

Step I.4: Implement the initiative

From the calculation of the theoretical benefit of this initiative at Plant X it was determined that the use thereof is limited. The implementation will consist of developing a notification tool to remind the scheduler of the benefits of using Ladle Furnace 2 as soon as the blast furnace is scheduled to operate at maximum production, as described in Step I.1.

Monitor production planning initiative

The *monitor* step of the methodology is verified by basing it on the *check* step of ISO 50001. During the practical application of the methodology it will be required to compile a baseline

and performance assessment method for each initiative, and to monitor its performance. For the theoretical application, however, such baselines are not used. The methodology made suggestions regarding the types of baseline method to use for each initiative. The other main focus of this step is to provide feedback on the performance of initiatives. Feedback reports for the implemented initiatives at Plant X should be distributed to the schedulers, production planners and plant management. The frequency and content of these suggested reports are as follows:

- Schedulers and production planners: Daily technical feedback on the achieved benefits and missed opportunities of the previous day; and
- Plant management: Weekly and monthly feedback on the performance of the initiative based on the baseline methodology.

Revise

The *revise* step of the methodology is the last step associated with ISO 50001, and is based on the *act* part thereof. The main purpose of this step is to achieve continual improvement on implemented initiatives, and it serves as a feedback loop to the *adapt/plan* step by using the feedback in the *monitor/check* step. Regular discussions with plant personnel are suggested to obtain their inputs based on the latest feedback, and to adapt the approach accordingly. Feedback discussions are suggested for the different entities at the following intervals:

- Schedulers and production planners: Weekly discussions regarding technical difficulties and concerns; and
- Plant management: Monthly discussions regarding general project performance and suggestions for improvements.

4.3.6. STEP 5: INTEGRATE AND MONITOR IMPLEMENTED PRODUCTION PLANNING INITIATIVES

Integrate implemented production planning initiatives

Overview

As per the methodology, initiatives are integrated by using an integration flow diagram (Figure 17). The flow diagram uses the latest casting and primary rolling priority lists, and calculates the potential benefit of each initiative. As the theoretical application is based on the 2016 data set, the theoretical benefit for each individual initiative was already calculated and discussed in Step E.5 of Section 4.3.3. In practice, integration of initiatives will occur on a daily basis

every time that a new schedule is received. A variation of the integration flow diagram for the theoretical application is presented in Figure 27.

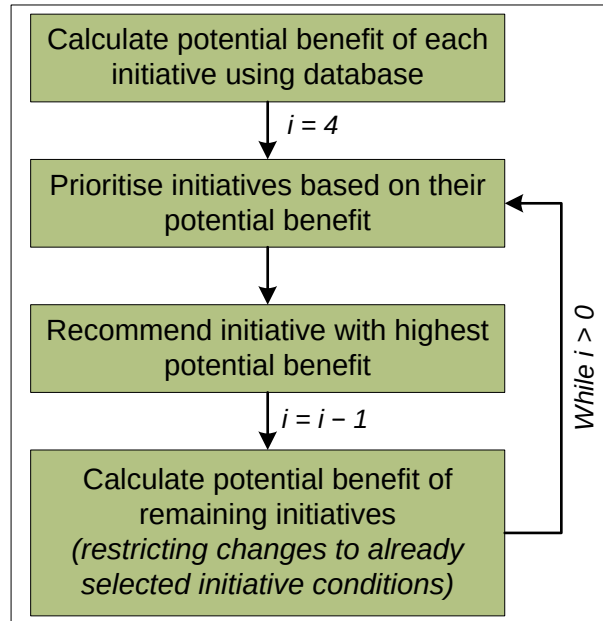


Figure 27: Basic integration of theoretical initiatives (based on Figure 17)

Based on the calculated potential benefit, the initiatives are compared and prioritised dynamically on a daily basis. This prioritisation is based on the largest potential benefit for the latest priority lists. The prioritisation was handled per virtual priority list for the 2016 data set in the theoretical application. The highest prioritised initiative is then given preference, but instead of using the previously calculated potential benefits for the remaining initiatives, the restrictions of the selected initiative are first considered in the calculation. The potential benefits of remaining initiatives are recalculated and initiatives are reprioritised. This process is repeated until the full potential benefit is utilised by all initiatives.

The focus of this discussion is to indicate the effect of using an integrated approach. To calculate the effect, the restrictions that the selection of an initiative contribute to the system have to be analysed. Such restrictions are mainly based on the practical constraints that were identified in Step E.4 of Section 4.3.3. In practice, it might be required for priority lists to be adapted and redistributed when such a change occurs. This is, however, not of relevance to the theoretical application of the methodology.

Effect of integration

It is not feasible to ignore the effect that the prioritisation of one initiative would have on another, and the practical restrictions need to be considered. For the purpose of the theoretical

application of the methodology on Plant X using 2016 data, the following restrictions were applied in the calculations:

- If a steel quality is flagged to be hot charged:
 - It cannot be scheduled for either load shifting initiative (schedules might have to be adapted to accommodate hot charging); and
 - The potential benefit of both load shifting benefits can then be calculated for the remaining steel qualities, but only one may be prioritised (load shifting cannot take place on both plants while hot charging also takes place);
- If a load shifting initiative is prioritised:
 - The steel quality should be removed from the potential hot charging list;
 - The benefits of the hot charging (without steel qualities scheduled for load shifting) and other load shifting initiative can be calculated, prioritising the initiative with the highest potential;
 - If hot charging has the highest potential of the remaining initiatives, the other load shifting cannot take place; and
 - If the other load shifting has a higher potential benefit than hot charging, it should be prioritised, but no hot charging may take place.

By implementing these restrictions into the calculations, the maximum integrated theoretical cost benefit for 2016 at Plant X was calculated. The daily cost benefit is presented in Figure 28. The yearly total theoretical cost benefit was calculated as R11.9 million.

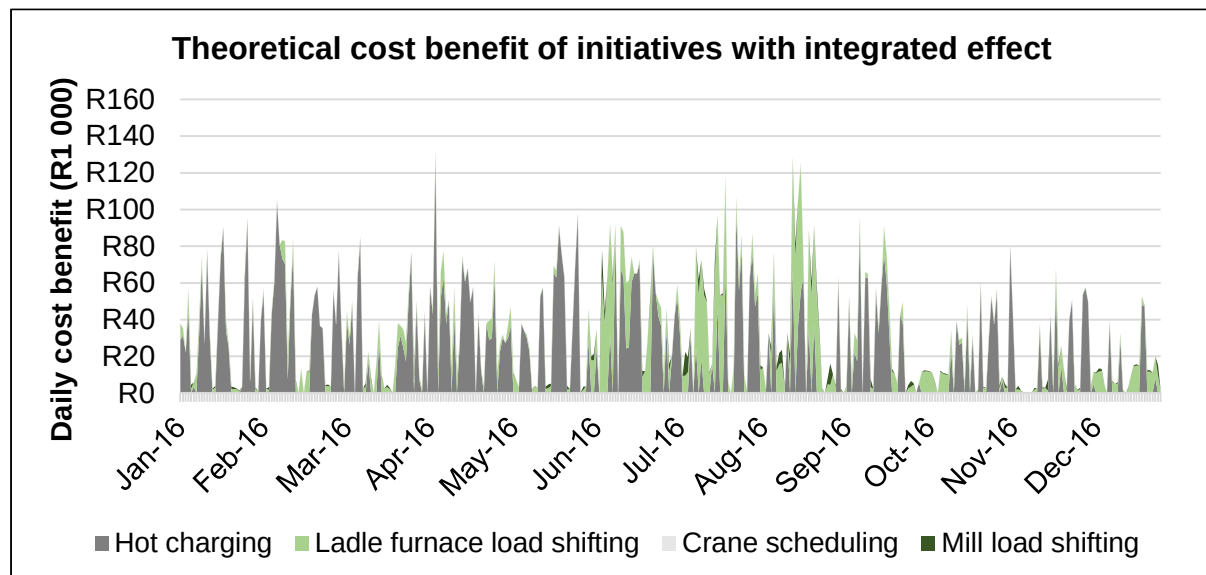


Figure 28: Theoretical cost benefit of integrated initiatives for 2016

Integrated effect comparison

To evaluate the effect of using an integrated approach, the expected result when an integrated approach is not an option has to be considered. If this was the case, Plant X would have only been able to implement one initiative rather than implement and integrate several initiatives. The most likely option from the static prioritisation of Section 4.3.4 would have been to only implement ladle furnace load shifting. Figure 29 compares the monthly cost benefit of only doing ladle furnace load shifting (non-integrated approach) and using the integrated approach based on 2016 data for Plant X.

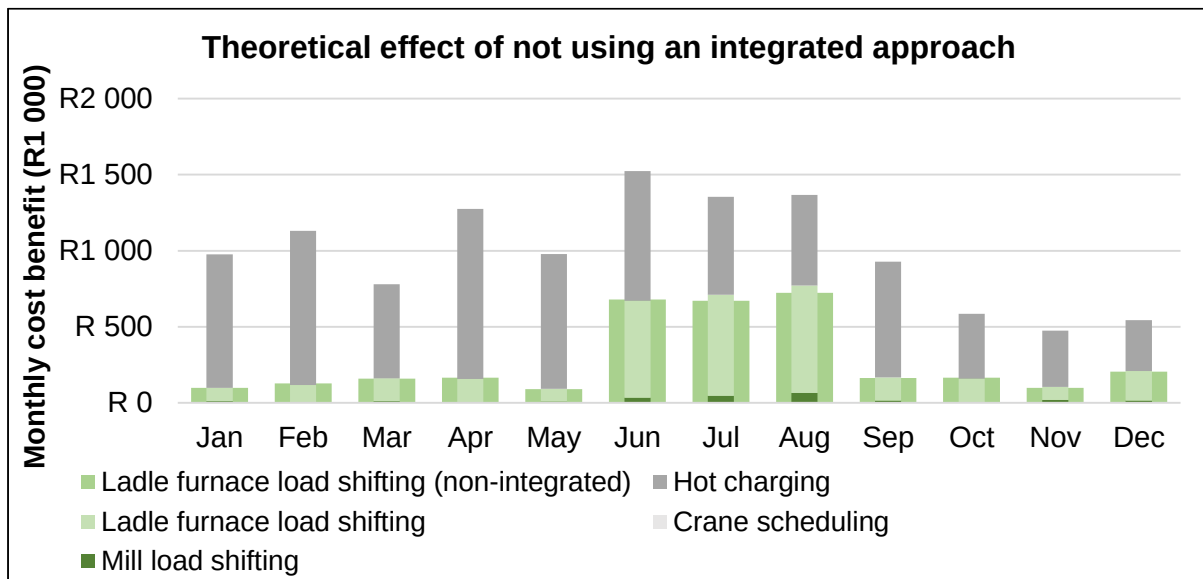


Figure 29: Monthly theoretical cost benefit effect of the integrated approach for 2016

An evaluation of the total yearly cost benefit for these two approaches is presented in Figure 30. From this comparison it is determined that the effect of using a non-integrated approach would have only resulted in 29% (R3.4 million) of the potential cost benefit than when using an integrated approach. Therefore, integration plays a critical role in the cost model for steel production planning.

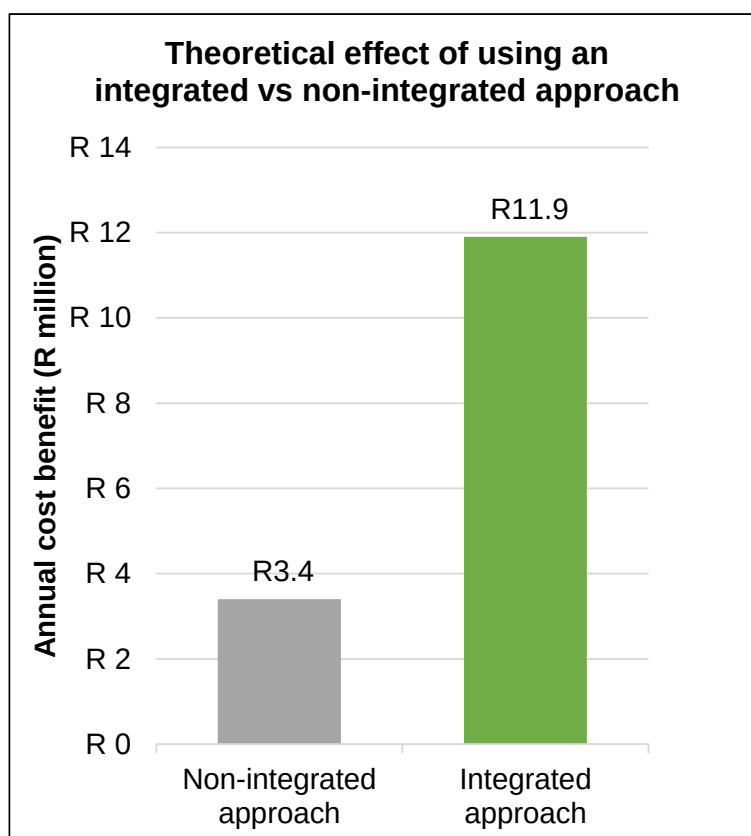


Figure 30: Theoretical effect of using an integrated approach

Monitor integrated production planning initiatives

The monitoring of the integrated approach is similar to the monitoring of individual initiatives, and is also considered as a variation of the *check* step of ISO 50001. This consists of monitoring the success of the integration. Depending on the initiatives that have already been implemented, the frequency, content and recipients of feedback reports have to be determined. It will not be necessary to compile a baseline for the integrated approach as with the individual initiatives, but the theoretical model can be used to compare actual performance with theoretical potential.

In terms of monitoring the theoretical benefit, Figure 31 provides a breakdown of the maximum theoretical cost benefit for the integrated initiatives on Plant X by using the 2016 data set. It is observed from this representation that the hot charging initiative would have contributed 71% of the cost benefit, the ladle furnace load shifting 27%, the mill load shifting 2%, and the crane scheduling initiative 0%.

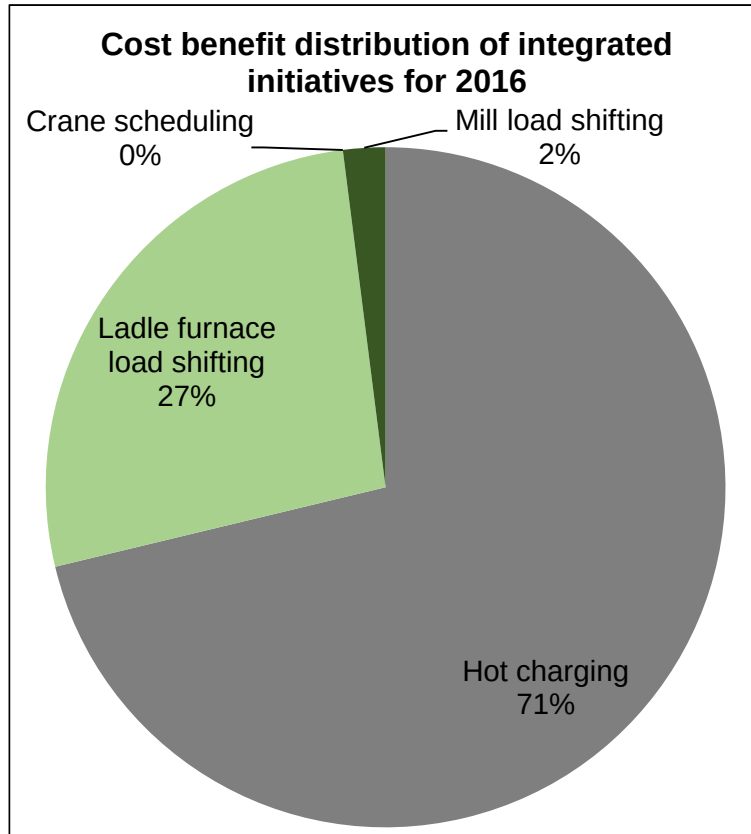


Figure 31: Theoretical cost benefit distribution of integrated initiatives for 2016

Revise

The last step in the methodology is a feedback loop to integrate implemented initiatives (*revise*), which is associated with the *act* step of ISO 50001. The purpose of this step is to revise the integrated approach based regarding the monitored performance and feedback from plant personnel.

The revision of the approach will mainly focus on adapting the restrictions that initiatives have on one another. It is possible that, through practical application of the methodology, some restrictions could be waived or that additional restrictions should be added. This step will lead to the continual improvement of the integration, thus ensuring that the maximum benefit is utilised from the integrated approach.

4.4. NOVEL CONTRIBUTIONS OF THE THEORETICAL APPLICATION

As with the previous chapter, the novel contributions of this chapter are revisited with reference to the contributions formulated and discussed in Section 1.4.

Contribution 1:

*Development of a **new cost model** for steel production planning by **adapting and combining multiple** industry applied methods*

In the theoretical application of the methodology, literature was used to identify five production planning initiatives that could potentially be implemented on Plant X. These initiatives were evaluated relative to Plant X, during which practical constraints were identified for the application thereof on the facility.

During the implementation of the methodology (ISO 50001), the *plan* step was represented by an *adapt* step. This discussion described how the initiatives and the implementation thereof had to be adapted from the approaches taken in literature to make them relevant to Plant X. The methodology allows for existing initiatives to be adapted in order to be relevant to a specific facility.

Focus was also placed on the integration of the initiatives during the theoretical application of the methodology on Plant X. Even though some steps (such as evaluation, adaption and implementation) take place separately for initiatives, the importance of the integrated approach was emphasised. The initiatives are first considered as an integrated entity when they are compared and prioritised (statically), and again later when they are prioritised dynamically. The importance of using an integrated approach was indicated, as it is likely that only one initiative would have been implemented if the option was not available. The new cost model achieved a theoretical cost benefit of R11.9 million compared with R3.4 million for a non-integrated approach.

Contribution 2:

*A **unique approach** for the **dynamic prioritisation** of multiple implemented initiatives*

A benefit quantification framework was developed during the evaluation of the theoretical potential benefit of the individual initiatives at Plant X. Different methods and data analysis techniques from literature were used as tools to ensure that the potential benefits of initiatives were quantified accurately. The importance of the accurate benefit quantification methods is to ensure that the static and dynamic prioritisation of initiatives are accurate, leading to the

utilisation of maximum potential benefits. The baseline methodologies were also briefly discussed, but will be considered in more detail in the next chapter.

The integration of initiatives was theoretically applied to Plant X using a variation of the dynamic prioritisation model. The dynamic prioritisation takes place continually every time that new information is made available. The prioritisation combines the maximum theoretical potential benefit of initiatives and practical constraints, and recommends the most beneficial scenario.

Contribution 3:

A uniquely adopted solution to address personnel-related resistance towards automated solutions at marginally profitable facilities

The developed methodology was verified by the theoretical application thereof on Plant X. This theoretical application included evaluating the practical constraints at the facility and therefore addressing some of the unique conditions of a marginally profitable steelmaking facility. Practical constraints were considered in the theoretical potential benefit quantification of initiatives, and further recommendations for the practical application were made during the implementation steps. The adaption of identified initiatives were used to adapt initiatives to the unique conditions. An ISO 50001-based implementation strategy was uniquely adopted to address the personnel-related resistance and practical constraints of the facility.

Contribution 4:

Novel integrated model for cost-efficient steel production planning

The novel integrated cost model developed in Chapter 3 was theoretically applied to a South African case study facility, Plant X, in this chapter. This theoretical application served as a verification of the developed methodology by confirming that it is possible to use the methodology to reduce the cost of steel production using an integrated production planning approach. The application used the actual processes and data of Plant X, and indicated how the unique constraints of such a facility are addressed by the methodology. The importance of using an integrated approach was emphasised by this application. It was verified that it is possible to improve the cost efficiency of steel production planning at a marginally profitable facility by using the novel integrated model.

4.5. CONCLUSION

This chapter served as verification that the methodology developed in Chapter 3 can be used to address the stated research objectives. The verification was conducted by the theoretical application of the developed methodology on a South African case study facility, namely, Plant X. The discussion started with an overview of the operations at Plant X, with specific focus on the production planning functions thereof. Each step of the methodology was verified using actual steelmaking facility data for 2016. The main outcome of the theoretical application was that only four of the five identified initiatives can be implemented on Plant X. It was determined that the implementation of the integrated approach would have resulted in a cost benefit of R11.9 million during 2016.

The use of the developed methodology as a cost model for steel production planning was verified by the theoretical application thereof. It was also seen that the use of a non-integrated approach would have only resulted in 29% of the cost benefit. Lastly, the novel contributions of the study were revisited with reference to the theoretical application. It was seen that the verification addressed all the novel contributions, thus confirming that the application of the methodology achieves the expected result. The next chapter will focus on a practical application of the methodology on Plant X, serving as validation thereof.

Chapter 5: Validation

The integrated cost model is proven to provide a valid solution to address the need for the study. This validation is achieved by the practical application of the methodology on a marginally profitable steelmaking facility.

5. VALIDATION OF THE INTEGRATED COST MODEL

5.1. INTRODUCTION

The new integrated cost model for steel production planning developed in Chapter 3 was verified in the previous chapter by the theoretical application thereof on Plant X. This chapter discusses the validation of this model by the practical application thereof on Plant X. The application of the methodology provides a valuable platform for a comparison between theoretical potential benefit and practically achievable benefits. A discussion of the results is included in this chapter based on such a comparison.

5.2. VALIDATION OF FACILITY RESULTS

5.2.1. PREAMBLE

The practical application of each step in the methodology is discussed in this sub-section as a validation of the methodology. Each step is discussed individually at the hand of the methodology developed in Section 3.2 (Figure 10 and Figure 11).

5.2.2. STEP 1: GATHER PRODUCTION PLANNING INFORMATION AND IDENTIFY PRODUCTION PLANNING INITIATIVES

Gather production planning information

Section 4.2 provided background to Plant X for a better understanding of the operations of the facility and its production planning functions. Further information on production planning at the facility was provided in Section 4.2.2, listing the inputs that production planners consider, and the information that they provide in the priority lists to plant schedulers. The sections discussed that priority lists are distributed on a daily basis to the two sections. The steelmaking priority list contains information for three days in advance, but the primary rolling priority list contains information for only one day. The practical application of the methodology used these priority lists as received on a daily basis.

Identify production planning initiatives for the facility

Five production planning initiatives were initially identified from literature in Section 2.4. From the theoretical evaluation, the remaining feasible initiatives for Plant X are:

- Hot charging of the primary rolling mill furnace;
- Ladle furnace load shifting;
- Ladle and crane time loss reduction; and
- Primary rolling mill load shifting.

5.2.3. STEP 2: EVALUATE PRODUCTION PLANNING INITIATIVES

Each identified initiative was evaluated individually in detail in Section 4.3.3. The evaluation of initiatives was sub-divided into five steps in the methodology (Steps E.1–E.5 in Figure 14), with a criterion to be selected for each step. A summary of the selected criterion per step for each initiative is provided in Table 23, based on the evaluation in the theoretical application.

Table 23: Summary of initiative evaluation

Step	Description	Hot charging of the primary rolling mill furnace	Ladle furnace load shifting	Ladle and crane time loss reduction	Primary rolling mill load shifting
E.1	Status	Implemented, but ineffective	Not previously considered	Not previously considered	Previous unsuccessful attempt
E.2	Data availability	All data sustainably available	All data sustainably available	Selective data available	All data sustainably available
E.3	Historical performance	Sufficient variation	Sufficient variation	Limited variation	Possible variation
E.4	Practical constraints	Sufficient variation	Possible variation	Possible variation	Possible variation
E.5	Potential benefit	Achieved if conditions allow it	Potential benefits exist	Limited potential	Potential benefits exist

5.2.4. STEP 3: COMPARE AND PRIORITISE PRODUCTION PLANNING INITIATIVES

Compare evaluated initiatives

The initiative ranking model was applied to Plant X during the theoretical application of the cost model in Section 4.3.4. The output of the initiative ranking calculation for each initiative, based on the criteria allocation provided in Table 23, is provided in Table 24. This was used to prioritise the implementation of initiatives.

Table 24: Initiative ranking based on evaluation of identified initiatives

Initiative	Initiative ranking
Hot charging of the primary rolling mill furnace	8
Ladle furnace load shifting	10
Ladle and crane time loss reduction	–2
Primary rolling mill apportionment model	–9
Primary rolling mill load shifting	5

Prioritise production planning initiatives

After evaluating the initiatives and applying the comparison model with results as presented in Table 24, the prioritised order for implementation was established. Ladle furnace load shifting is the highest prioritised initiative in the ranking. In the theoretical application in Chapter 4, however, it was seen that hot charging the primary rolling mill furnace has a larger theoretical cost benefit.

The number of times that an initiative was theoretically prioritised for having the highest potential cost benefit was analysed. Figure 32a shows that the hot charging initiative was prioritised 6% more than ladle furnace load shifting during 2016. When isolating the winter months of 2016 in Figure 32b, however, it is seen that ladle furnace load shifting outweighed the hot charging initiative by 14%. This highlights the increased potential benefit of load shifting in winter months due to the higher electricity tariffs.

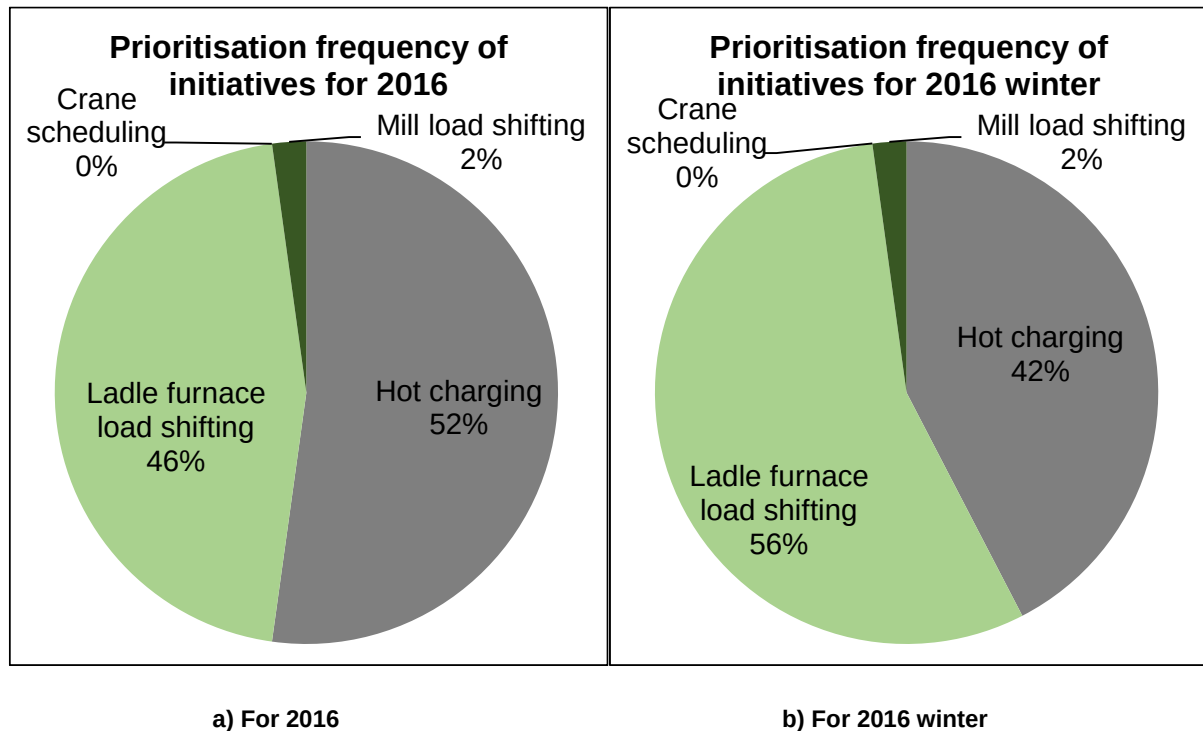


Figure 32: Prioritisation frequency of integrated initiatives

These results indicate that it would be more beneficial to prioritise ladle furnace load shifting if the implementation date is closer to the winter TOU period (starting in June). The practical implementation of the cost model on Plant X commenced during April 2017. With the consideration of developing implementation tools, baseline discussions with plant personnel, and the practical implementation of initiatives, it was determined that there would only be time to implement one initiative before the winter period. It was decided not to make exceptions to

the initiative prioritisation discussed in Section 4.3.4. Therefore, the practical implementation of *ladle furnace load shifting* initiative was prioritised.

5.2.5. STEP 4: IMPLEMENT PRODUCTION PLANNING INITIATIVES (ISO 50001)

Adapt production planning initiative

Overview

The next four steps of the methodology (*adapt-implement-monitor-revise*) are based on the PDCA approach of ISO 50001 and form part of the ISO 50001-based implementation strategy of the methodology. The practical steps to be followed to implement each of the initiatives were discussed in the theoretical application, but the steps were not developed or implemented practically. The validation in this chapter focuses mainly on the practical implementation of the initiatives. Two of the initiatives were practically implemented at Plant X as a validation of the developed methodology. The practical implementation dates of the two initiatives are listed in Table 25.

Table 25: Practical implementation dates of initiatives

Initiative	Implementation date
Ladle furnace load shifting	1 July 2017
Hot charging of the primary rolling mill furnace	1 March 2018

Ladle furnace load shifting

The ladle furnace load shifting initiative was derived from a combination of initiatives evaluated from literature. The concept is based on electrical load shifting of an EAF, which is also a large consumer of electrical energy in steelmaking. The EAF can, however, be delayed as needed to adapt to TOU periods, whereas the ladle furnace in the BF-BOF process cannot. Ladle furnace load shifting is based on processing lower energy intensive steel qualities during periods with higher tariffs rather than delaying production during such times.

The application of initiatives at Plant X poses further difficulties due to the plant being a marginally profitable facility located in South Africa. The automated methods suggested for the application on the EAF could not be used for this application, and it was decided to use an ISO 50001-based implementation strategy instead. This consisted of training personnel to rather schedule lower energy intensive steel qualities during peak times. This was done by developing assistive tools and flagging systems, and training schedulers and production planners to use these tools. The implementation during this practical implementation was adapted to consist of developing and presenting these tools, and by providing information on how the training of personnel commenced.

Hot charging of the primary rolling mill furnace

Similar to ladle furnace load shifting, the hot charging of the primary rolling mill furnace was also implemented at Plant X by using the ISO 50001-based implementation strategy. This is an adaption from the strategies identified in literature where automated systems were used to schedule production to incorporate hot charging. Plant X has all of the infrastructure available for hot charging, and it already takes place. The focus of the initiative is therefore on increasing the amount of steel that is hot charged into the primary mill furnace. The implementation of the initiative will resolve the challenges currently causing a lack of optimal hot charging.

Implement production planning initiative

Overview

The implementation of the production planning initiatives consists of four steps, as discussed during the development of the methodology (Steps I.1–I.4 in Figure 16 in Section 3.2.5). Suggested methods for creating and using each step were briefly addressed during the theoretical application of the methodology. The actual tools for the practical application of this step are developed and presented in this discussion and the accompanying appendices.

Ladle furnace load shifting

Step I.1: Compile and simplify assistive tools for production planning to use

The assistive tools developed for ladle furnace load shifting allow schedulers and production planners to utilise opportunities. The first assistive tool provided to schedulers and production planners were reference sheets indicating the preferred steel qualities during peak time production, which are based on the energy intensities of different steel qualities listed in Appendix D. Figure 33 shows an example of the reference sheet for Production Route 2 steel qualities (Production Route 3 steel qualities are therefore not seen in this reference sheet).

Steelmaking time of use production planning for Route 2 steel qualities				
Alphabetical list of Route 2 steel qualities		Steel qualities in order of electrical energy consumption		
Steel quality	Prefered period	Steel quality list		
Quality 1		Peak preferred	Peak safe	Critical non-peak
Quality 3		Quality 16	Quality 81	Quality 88
Quality 5		Quality 19	Quality 35	Quality 22
Quality 15		Quality 85	Quality 17	Quality 1
Quality 16		Quality 24	Quality 76	Quality 66
Quality 17		Quality 20	Quality 26	Quality 72
Quality 18		Quality 18	Quality 31	Quality 80
Quality 19		Quality 78	Quality 25	Quality 44
Quality 20		Quality 21	Quality 87	Quality 15
Quality 21		Quality 73	Quality 23	Quality 42
Quality 22		Quality 5	Quality 37	Quality 75
Quality 23		Quality 27	Quality 36	Quality 3
Quality 24		Quality 46		Quality 41
Quality 25				
Quality 26				
Quality 27				
Quality 31				
Quality 35				
Quality 36				
Quality 37				
Quality 41				
Quality 42				
Quality 44				
Quality 46				
Quality 66				
Quality 72				
Quality 73				
Quality 75				
Quality 76				
Quality 78				
Quality 80				
Quality 81				
Quality 85				
Quality 87				
Quality 88				

TOU tariff times			
Hour	Weekday	Saturday	Sunday
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			

*Production should not be scheduled during peak time at all if possible.

Figure 33: Ladle furnace load shifting Production Route 2 steel qualities reference sheet

This example shows that an alphabetical list is provided to schedulers to easily find the time period in which to produce a specific steel quality. Steel qualities presented in a specific colour are preferred to be produced in the time period represented by that colour (for example, green coloured steel qualities are preferred in off-peak times, i.e. high energy intensive). Another list with the same steel qualities is also included, which groups steel qualities in order of their energy intensity. This can be used if the scheduler has to decide between steel qualities in the same group. A similar type of reference sheet was compiled for Production Route 3 steel qualities.

The next tool that was developed for schedulers is an online interface where planned schedules can be adapted and compared. This provides the opportunity to evaluate the theoretical effect of changes to the planned schedule. A simplified view of the conceptual online interface is provided in Appendix H.1. A screenshot of the inputs of the online interface is presented in Figure 34 (steel qualities were removed due to confidentiality reasons). The inputs for the interface are two suggested schedules, specifying the suggested production time of each steel quality, and the production route of the steel quality. The liquid iron level and blast furnace production rate at the time are also provided as inputs for the system.

The output of the online interface provides the estimated effect on the available liquid iron level to ensure that the required boundaries are maintained. The expected TOU period cost distribution for the next three days is provided along with an accumulated cost of electrical energy for the three days. The costs are compared with the output of the second schedule, and the comparison is used to determine the most cost-effective production schedule. This provides schedulers with the opportunity to evaluate the possible effects of changes and to ensure that the most beneficial schedule is used. This is illustrated in the simplified view of the conceptual online interface in Appendix H.1

Modifications were also made to the production priority list distributed by the production planner responsible for the steelmaking section. This list was modified to include an indication of the TOU periods, and to indicate the preferred time period of the steel qualities on the list. This enabled production planners to already evaluate the preferred scenarios before distributing the priority list.

Adjusted schedule					
Casting time	Ladle furnace 1		Ladle furnace 2		Liquid iron level [tonne]
	Steel grade	Route	Steel grade	Route	
2017-07-25 12:00					1025
2017-07-25 13:00					1050
2017-07-25 14:00		2			1075
2017-07-25 15:00		2			1100
2017-07-25 16:00		2			1125
2017-07-25 17:00		2			1150
2017-07-25 18:00		2			1174
2017-07-25 19:00		2			1058
2017-07-25 20:00		2			1083
2017-07-25 21:00		2		2	1107
2017-07-25 22:00				2	1132
2017-07-25 23:00		2			1016
2017-07-26 00:00		2			1040
2017-07-26 01:00		2		2	1065
2017-07-26 02:00		2			949
2017-07-26 03:00		2			832
2017-07-26 04:00		2		2	857
2017-07-26 05:00		2		2	882
2017-07-26 06:00		2			906
2017-07-26 07:00		2			931
2017-07-26 08:00		2			815
2017-07-26 09:00		2			839
2017-07-26 10:00		2		2	1006
2017-07-26 11:00				2	1031
2017-07-26 12:00					1056
2017-07-26 13:00		2			1081
2017-07-26 14:00		2			1106
2017-07-26 15:00		2			1131
2017-07-26 16:00		2			1156
2017-07-26 17:00		2			1181

Figure 34: Ladle furnace load shifting online interface input sample

Wall clocks, as presented in Figure 35, were installed in control rooms to show the current and next TOU periods. The example in Figure 35 was used as the background of a standard wall clock, providing a live indication of TOU periods in a practical way. Assuming that it is in the afternoon, the example in Figure 35 indicates that it is currently peak time (between 18:00 and 19:00), and that the next TOU period is standard time (from 19:00).

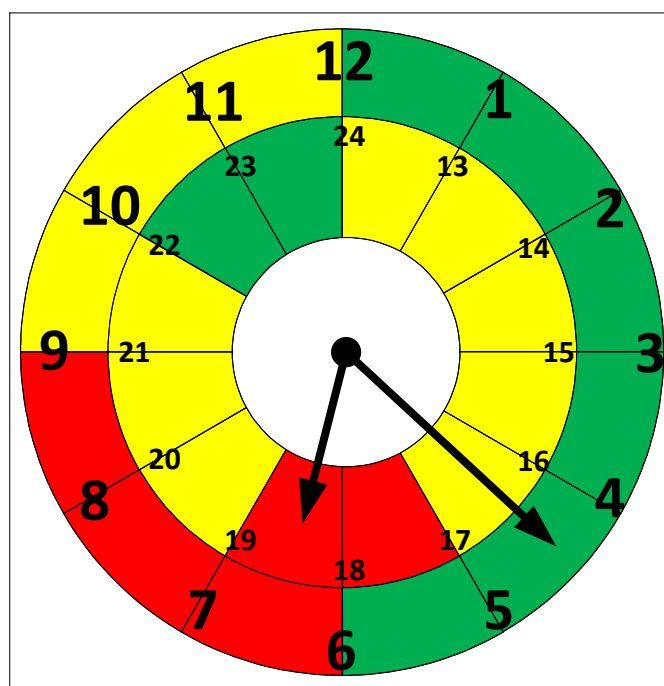


Figure 35: TOU wall clock example

Step I.2: Create awareness by highlighting and discussing benefits

The theoretical potential benefits of ladle furnace load shifting was discussed with all involved parties at the hand of the information sheet presented in Appendix H.2. The information sheet was populated with several of the calculated theoretical potential benefit graphs, as discussed in Appendix B.3. The discussion of these benefits was accompanied by suggestions of how ladle furnace scheduling can be achieved practically, as listed below:

- Cast on both casters during off-peak time (nights and weekends) to lower the liquid iron level at the start of peak time;
- Schedule only one ladle furnace in peak times if possible (use torpedoes for small delays); and
- Only change BOF tap holes during peak times.

Step I.3: Create an assistive system to flag opportunities

A report was developed to flag opportunities for ladle furnace load shifting based on the latest priority list distributed by the production planner. An example of such a flag report is presented in Appendix H.3. The flag report is important to indicate the highest and lowest energy intensive steel qualities on the latest priority list. The potential savings of the best-case versus worst-case scenarios are also included in the flag report. This served as a reminder for schedulers to consider load shifting when scheduling production. It further indicated what the most beneficial conditions would be for the initiative.

Step I.4: Implement the initiative

The last step of the implementation phase of each initiative is to apply the initiative practically on Plant X using the tools developed in the previous steps. A log was kept of the main practical application steps during this phase, as provided in Appendix H.4.

Hot charging of the primary rolling mill furnace

Step I.1: Compile and simplify assistive tools for production planning to use

Due to the hot charging of the primary rolling mill furnace being an existing initiative, the development of assistive tools focused on enhancing existing methods. An online interface was developed to evaluate scenarios (a simplified version is presented in Appendix I.1). The purpose of this interface is to provide all of the planned steel qualities to be produced on a day as the input, indicating which of them are planned to be hot charged. An estimated theoretical potential benefit is then calculated along with the estimated missed opportunities of not reaching the 40% targeted hot charge.

Step I.2: Create awareness by highlighting and discussing benefits

To create awareness towards the benefits of increased hot charging, all the involved parties were presented with information sheets of the potential benefits. This was done by using a presentation to highlight the potential benefits. The information sheet and presentation used the theoretical potential benefit calculations discussed during the theoretical application of the methodology on Plant X. The information sheet and presentation are provided in Appendix I.2.

Step I.3: Create an assistive system to flag opportunities

The flagging system developed for the hot charging initiative requires both the steelmaking and primary rolling mill priority lists. As soon as a new primary rolling mill priority list was distributed, it was compared with the latest steelmaking priority list, and communal steel qualities appearing on both lists were flagged. The flag report was distributed to production planners and the relevant primary rolling mill personnel. This flag report took steel qualities that were already scheduled to be hot charged into account. This report indicated the potential benefit of utilising all of the flagged opportunities, and the missed opportunities of only hot charging the planned steel qualities. An example of such a report is presented in Appendix I.3.

Step I.4: Implement the initiative

As with the implementation of ladle furnace load shifting, a log of the main practical application events was kept for the hot charging initiative. The log is provided in Appendix I.4 and serves as a representation of the causality of the achieved performance of the initiative.

Monitor production planning initiative

Ladle furnace load shifting

Baseline

The first aspect of monitoring the practical application of an initiative is to develop a baseline to assess its performance. The baseline period for ladle furnace load shifting was selected as the six calendar months prior to implementation. The extensive baseline period ensures that a variety of scenarios are taken into account, which eliminates irregular patterns caused by daily variances. The baseline was developed from data for the period from 1 January 2017 to 30 June 2017 (the six months preceding the practical application). As per the methodology, it was decided to use an energy-neutral daily power profile as the baseline for this initiative. Demand profiles consist of the average half-hourly MWh values for the pre-implementation period, converted to hourly power values in MW, as presented in Figure 36.

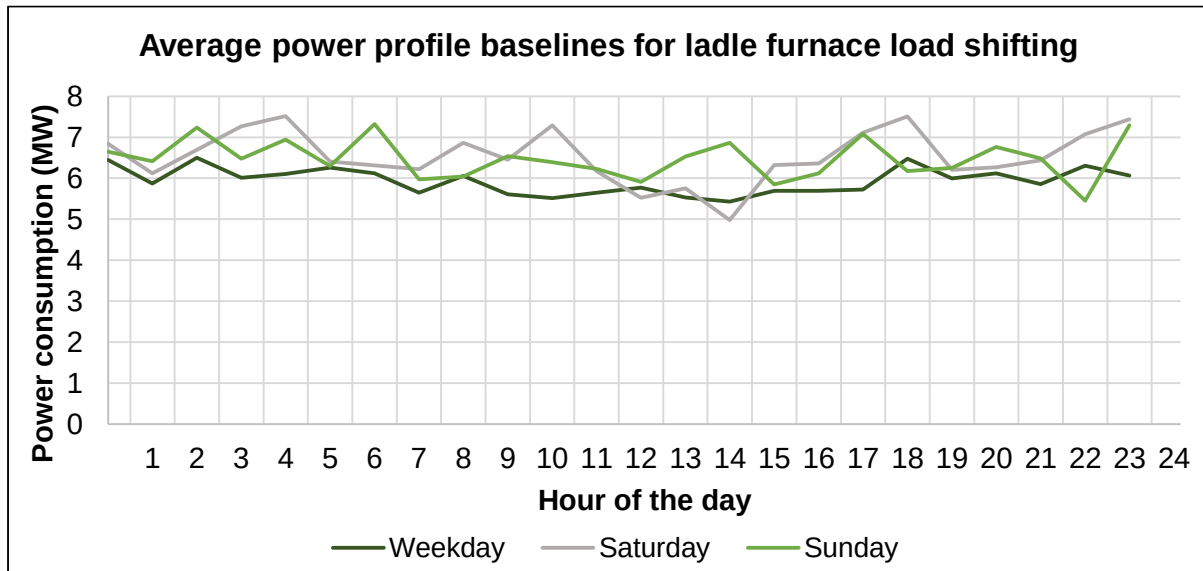


Figure 36: Ladle furnace load shifting baseline average daily power profiles

The total daily energy consumption values for the profiles in Figure 36 are: average weekday (142 MWh), Saturday (157 MWh) and Sunday (155 MWh). It was further decided to use weekly energy-neutral baseline adjustments to ensure that the post-implementation consumption was comparable to the baseline profile. Weekly scaling was used to account for the possible movement of higher energy intensive steel qualities to weekends to prevent peak time energy consumption. The calculation for adjusting each data point in the power profiles of Figure 36 is provided in Equation 7.

Equation 7: Baseline adjustment for weekly energy-neutral scaling

$$\text{Adjusted baseline} = \text{Baseline} \times \frac{\text{Actual total weekly energy consumed}}{\text{Baseline total weekly energy consumed}}$$

The actual post-implementation daily electrical energy cost was subtracted from the adjusted baseline electrical energy cost for the ladle furnaces to quantify the achieved cost savings by using Equation 8.

Equation 8: Daily cost saving calculation for ladle furnace load shifting

$$\begin{aligned} \text{Daily cost saving [R]} \\ &= \text{Adjusted baseline electrical energy cost [R]} \\ &\quad - \text{Actual electrical energy cost [R]} \end{aligned}$$

Project performance was assessed on a weekly basis as the actual total weekly energy consumption was required for baseline adjustment.

Assessment

The second aspect of monitoring the practical implementation of initiatives is to assess the performance and provide feedback to plant personnel. The feedback reports differ depending on the recipients thereof. The first form of feedback is a daily report that is distributed to schedulers and production planners on weekdays, as presented in Appendix J.1. This report provides feedback on the power profile and TOU cost distribution of the different sections of the entire steelmaking section for the previous day. The TOU cost distribution is provided for the previous two weekdays.

The purpose of this report is for the production planner and scheduler to understand the cost value of electricity, and to see the effect that ladle furnace load shifting has on all sections of steelmaking. It is also possible for schedulers to compare the cost effect of the past two days, keeping in mind what they did differently between the two days to achieve the results. This makes it possible for schedulers to associate practical behaviour with improved performance, enabling them to replicate it.

A weekly baseline scaling feedback report was distributed every Monday; an example is presented in Appendix J.2. This report was provided to plant management as feedback on the performance of the initiative for the past week, as measured against the baseline. This not only provided a way to monitor the effect of the weekly energy-neutral baseline scaling, but also indicated the performance of the initiative. It enabled plant management to see when performance declined and to act accordingly. Any changes to the implementation strategy could be adapted on a weekly basis to ensure that the performance of the initiative was well

maintained. An example of the weekly baseline scaling graph that appeared in this report is presented in Figure 37.

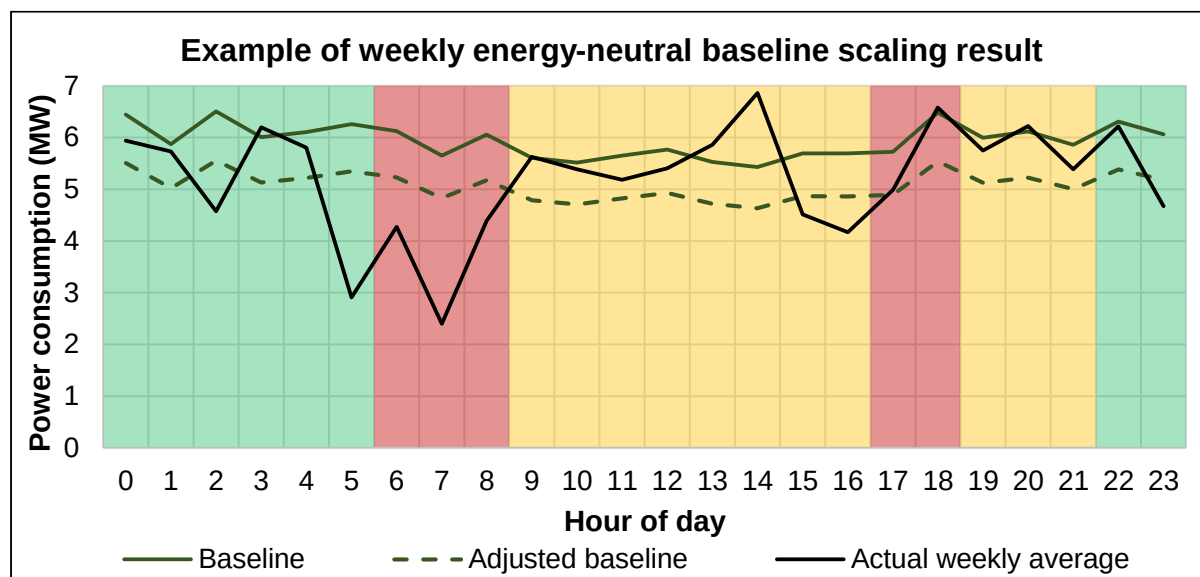


Figure 37: Example of weekly energy-neutral baseline scaling (7 to 16 July 2017)

Shift rating reports were provided to plant management on a weekly basis, with an example presented in Appendix J.3. These reports were used by plant management to compare the performance of different schedulers, and served as an indication of which schedulers had the most effective approach towards practically applying the initiative. The indication of the performance of different shifts could then be used to exchange ideas between schedulers, thereby improving the general performance of the initiative.

A monthly cost benefit summary report is presented in Appendix J.4, which was distributed to plant and works management. This provided feedback on the general status of the initiative, and was used for budgeting purposes. This enabled Plant X to monitor the performance of the initiative on a high level, and to use it to provide feedback to all stakeholders on steps that were taken for energy cost reduction. From an overall facility management point of view, it served as a platform to discuss ideas and concepts with other sections on the facility, and to obtain independent inputs from management. The detail in this report was kept to a minimum, and only cost reduction effects were highlighted.

The performance of the initiative was monitored from its implementation on 1 July 2017 until 30 April 2018, with the daily cost benefit of the practical application presented in Figure 38. The comparison between this result and the daily theoretical cost benefit presented in Figure 25 (Section 4.3.3) shows that the achieved cost benefit is less than the originally estimated benefit. This is mainly due to the theoretical estimation using the maximum potential benefit for each day, while this was not always practically achievable. The basic concept is, however,

validated by this result, and similarities are observed, such as the increased effect during winter periods (July and August 2017 on Figure 38). It is also important to note that the hot charging initiative was implemented during March and April 2018.

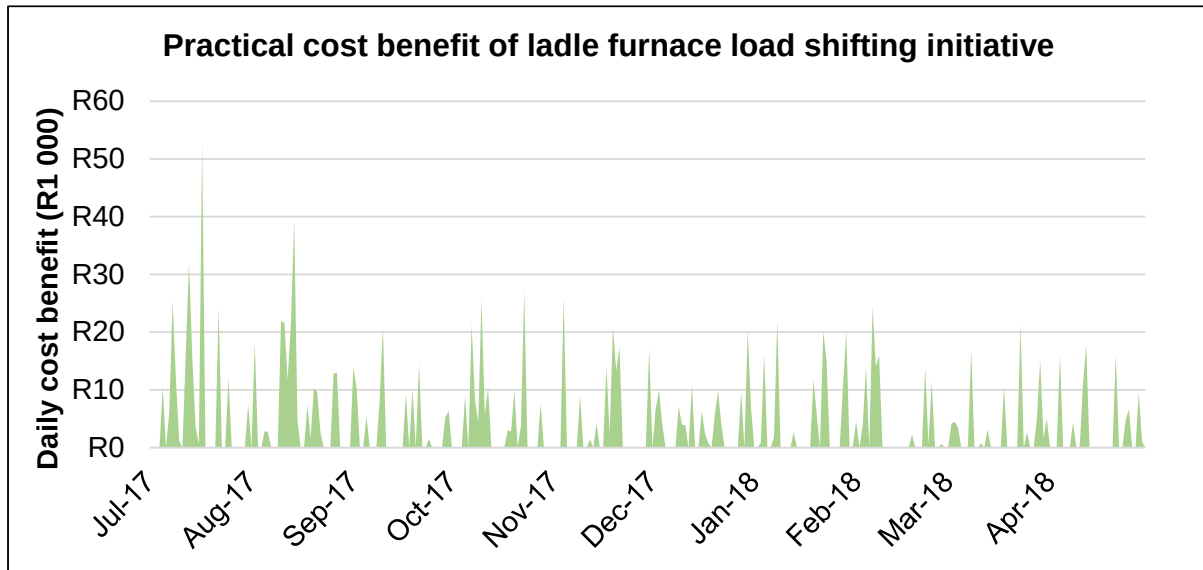


Figure 38: Practical daily cost benefit of ladle furnace load shifting implementation

The monthly cost benefit of the practical application of the initiative at Plant X is presented in Figure 39. This representation shows the larger cost benefits during the winter months more clearly for July and August 2017. It is also observed that the cost benefits for March and April 2018 are the lowest of all the months, thereby indicating the interactive effect that integrated initiatives have on one another. The total cost benefit for the 10-month implementation period of this initiative was R1.3 million.

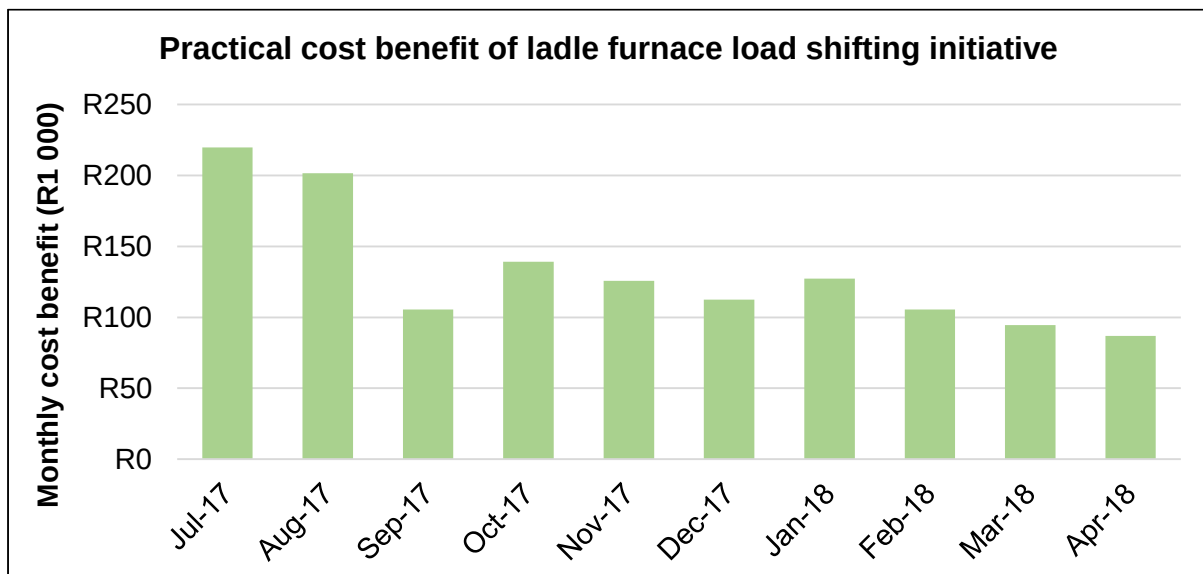


Figure 39: Practical monthly cost benefit of ladle furnace load shifting implementation

Hot charging of the primary rolling mill furnace

Baseline

A regression model was suggested as the baseline method for the hot charging of the primary rolling mill furnace at Plant X during the development of the methodology. Upon discussions with plant personnel it was identified that some steel profiles are not suitable for hot charging, and had to be removed from the data analyses. These profiles are listed in Table 26. Most of these profiles are deemed condonable due to the typical production tempo thereof being slower and the profiles not being feasible for hot charging. A day was therefore deemed condonable if more than 50% of the tonnes produced consisted of these condonable profiles.

Table 26: Hot charging condonable profiles

Description	Condonable profiles
Slab blooms	Profile 2
	Profile 5
	Profile 14
Slow processing profile	Profile 23
Rectangular profile	Profile 13
Round profile	Profile 12
	Profile 16
	Profile 20
	Profile 21
Degasser steel qualities	Profile 8
	Profile 9
	Profile 19

After removing the condonable days, a suitable baseline period had to be determined. To consider the performance of the furnaces under different conditions, the data set was divided into different configurations. These configurations considered the number of furnaces in use and the type of gas (COG or natural gas) used by the furnace each day. If only one furnace was used on a day, the furnace also had to be specified. Due to the mixing of gases that take place in the furnaces, a day was allocated to a specific gas if it consumed more than 50% thereof. The number of data points in each configuration for different baseline periods is presented in Figure 40. It was established that there had to be enough data to represent one month (30 days) for each configuration.

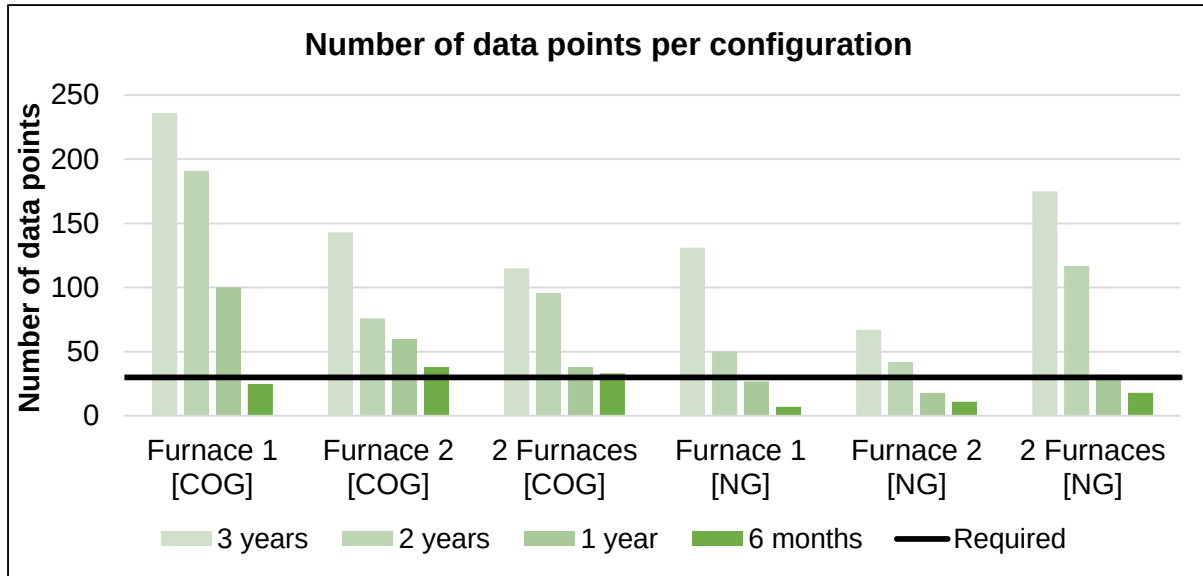


Figure 40: Number of data points for different hot charging baseline periods¹⁰

A two-year baseline period was selected from Figure 40 as this period consisted of at least 30 days per configuration. The baseline was selected as the two years preceding the implementation of the initiative (1 March 2016 to 28 February 2018). From this data set, a regression model was generated for each configuration, with a summary presented in Figure 41. The development of each individual regression model is provided in Appendix K.1.

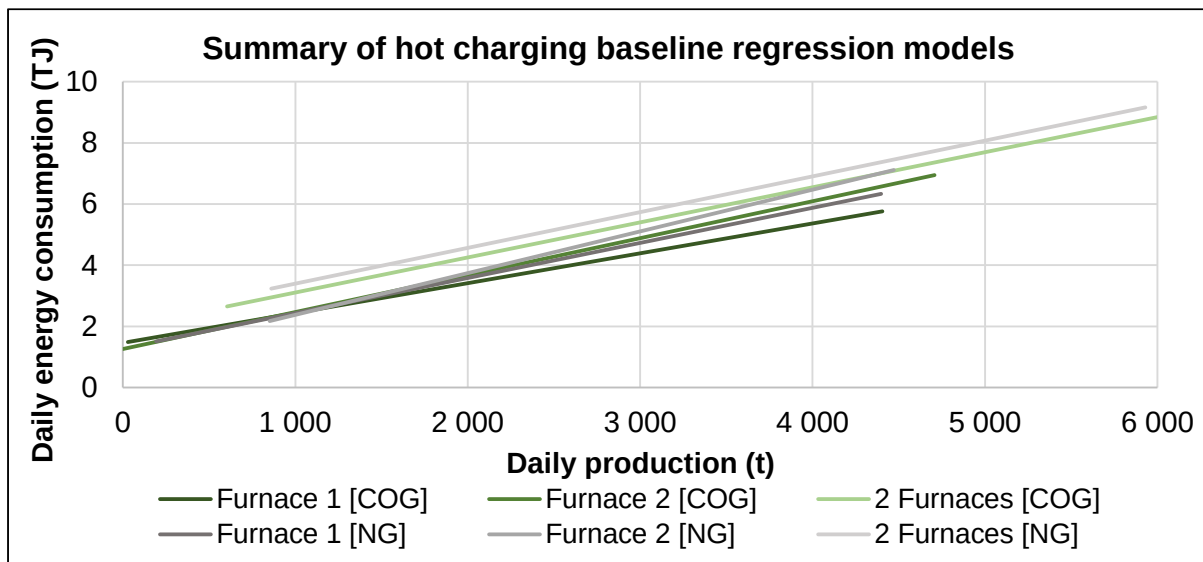


Figure 41: Summary of hot charging baseline regression models

Table 27 lists the straight line formula constants (Equation 4 in Section 2.5.5) along with the correlations of the data set relevant to the regression lines (R^2 values) and the number of data points. The table shows that the lowest correlation is 79% for Furnace 1 using more than 50%

¹⁰ Natural gas is referred to as NG in graphs.

COG. This is an acceptable correlation, and the regression lines presented in Figure 41 were accepted as the baseline for the initiative at Plant X.

Table 27: Hot charging baseline regression model characterisation

Description	Gradient (m)	Constant (c)	R ²	Data points	Line colour
Furnace 1 (COG)	0.98	1 456	79%	191	
Furnace 2 (COG)	1.21	1 261	93%	76	
2 Furnaces (COG)	1.15	1 959	82%	96	
Furnace 1 (natural gas)	1.15	1 289	88%	50	
Furnace 2 (natural gas)	1.36	1 015	94%	42	
2 Furnaces (natural gas)	1.17	2 221	82%	117	

Hot charging, however, has taken place at Plant X before, and the purpose of the initiative is to increase the amount of hot charging the primary rolling mill furnaces. It was agreed that the cost benefit for the initiative was only recognised if the hot charging rate for a month exceeded that of the baseline period. A summary of the total tonnes produced and hot charged during the baseline period is presented in Table 28, from which the baseline hot charging rate was calculated as 26%.

Table 28: Summary of key indicators for hot charging baseline

Parameter	Value
Production (t)	1 955 930
Hot charging (t)	509 329
Hot charging rate (%)	26%

Assessment

The hot charging of the primary rolling mill furnace at Plant X was assessed by using this baseline method, and was monitored using several feedback reports. The first report was distributed daily to production planners and primary rolling mill personnel, which reported on the performance of the previous week-to-date. An example of such a report is provided in Appendix K.2, which consists of the hot charging rate for the week-to-date, as well as the change from the previous weeks. The month to date performance is also indicated in this report.

The missed opportunities of the day are calculated by comparing the steel qualities that were casted with those processed by the primary rolling mill. Steel qualities that were casted but not hot charged were identified as missed opportunities. An estimation of the possible effect

of hot charging this steel was calculated by using the theoretical benefit calculation methods developed in the theoretical application of the methodology.

As with the ladle furnace load shifting initiative, weekly shift rating reports were distributed to plant management, with an example presented in Appendix K.3. These reports include the total hot charging rate, the cost saving achieved for the past week, as well as the performance of the different shifts. This made it possible to monitor the performance and to evaluate which shifts had more successful results in achieving higher hot charging rates. The shifting rate reports evaluated the production planning and primary rolling mill shifting personnel. This provided a platform for discussions with different shifts to exchange suggestions for the initiative.

Lastly, monthly cost benefit summary reports were distributed to plant and works management, as presented in Appendix K.4. As with the ladle furnace load shifting initiative, these reports were used to monitor the performance on a monthly basis, which served as a platform for discussions with stakeholders. These reports consist of more detail regarding hot charging performance, and monitor whether the hot charging rate for each month exceeded the required 26%. The hot charging of the primary rolling mill furnace was applied practically at Plant X for March and April 2018, with a summary of the results presented in Table 29. This summary shows that the hot charging rates for both months exceeded 26%, and that an energy cost reduction was achieved during both months.

Table 29: Summary of hot charging practical application results

Parameter	March 2018	April 2018
Production (t)	112 627	60 041
Hot charging (t)	36 700	21 820
Hot charging rate (%)	33%	36%
Hot charging (t)	7 744	24 273
Energy cost reduction	R480 000	R1 500 000

Figure 42 presents the practical daily cost benefit for the two months of implementation. The figure shows that a large benefit was achieved during the second month of implementation. This is mainly allocated to the continuous improvement achieved by the implementation and the revision of implementation strategies. The achieved benefit is slightly higher than the theoretically predicted performance in Figure 24 (Section 4.3.3) as the baseline model considered different operational configurations of the furnace, while the theoretical estimations aimed to provide a general indication of the potential benefits. The cost benefit achieved for the two months of implementation is R1.98 million.

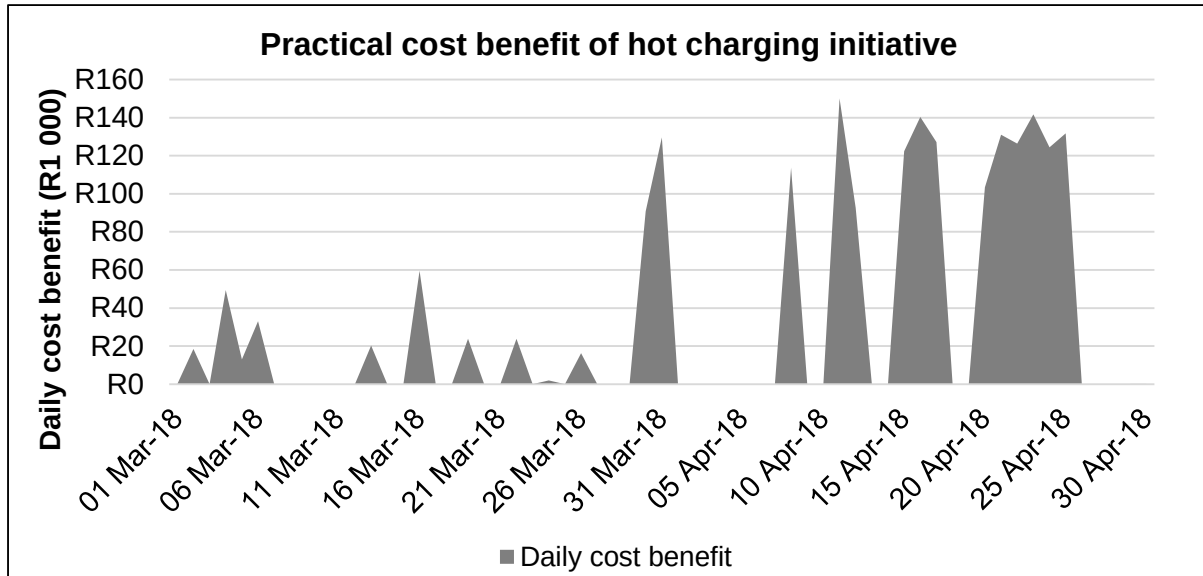


Figure 42: Practical daily cost benefit of hot charging implementation

Revise

The practical implementation strategies of both initiatives were monitored continually, as discussed in the previous section. Regular discussions with Plant X management and feedback discussions with personnel executing the practical implementation were used as communication channels between stakeholders, which led to revisions of the implementation strategies. This served as the *act* step of the ISO 50001 implementation process, which ensured that concerns raised by the stakeholders were addressed in a timely manner. Revisions of the methods entailed incorporating several elements throughout the implementation, and refining the methods and approaches that were used.

5.2.6. STEP 5: INTEGRATE AND MONITOR IMPLEMENTED PRODUCTION PLANNING INITIATIVES

Integrate implemented production planning initiatives

The integration of practically implemented initiatives at Plant X was required to ensure that the most beneficial conditions were prioritised, as discussed in the methodology. The prioritisation was incorporated into the flagging reports provided to personnel as discussed in Section 5.2.5 (Appendix H.3 and Appendix I.3 provide examples of the flag reports for the initiatives). The initiatives were integrated by using the dynamic prioritisation approach presented in Figure 43 whenever new priority lists were provided, as derived from Figure 17.

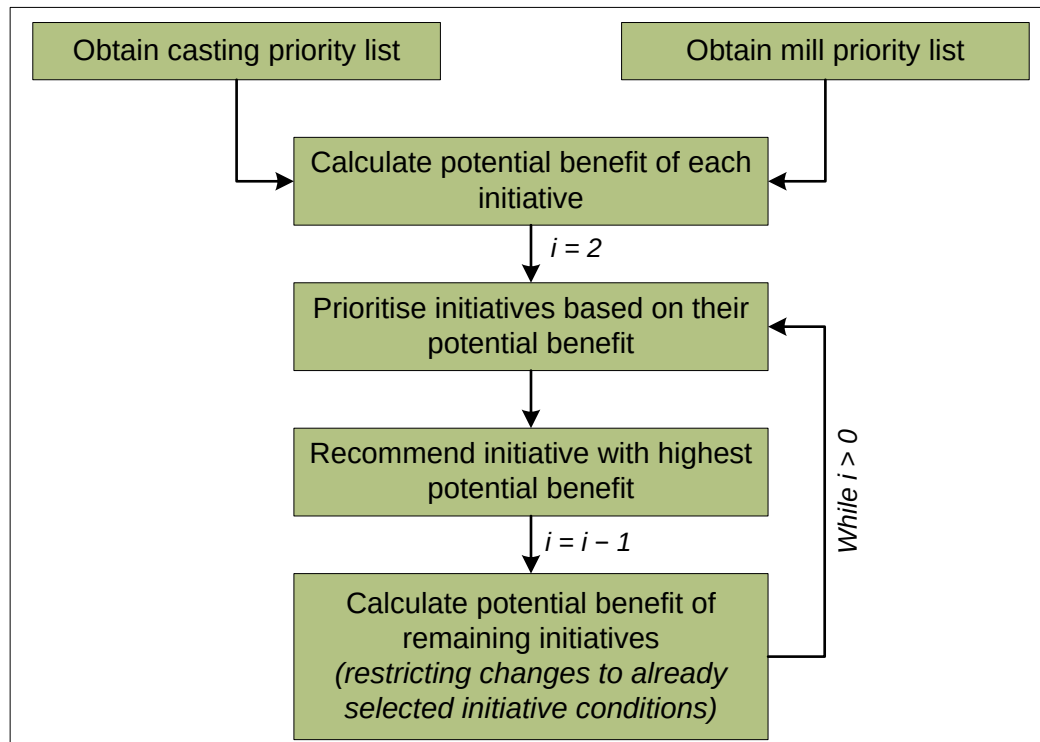


Figure 43: Basic integration of practically implemented initiatives (based on Figure 17)

Using the conceptual prioritisation of Figure 43, a flow diagram for the practical integration of initiatives was developed, which is presented in Figure 44. This flow diagram was incorporated into the flagging reports provided to different parties to indicate what conditions should be prioritised at a given time.

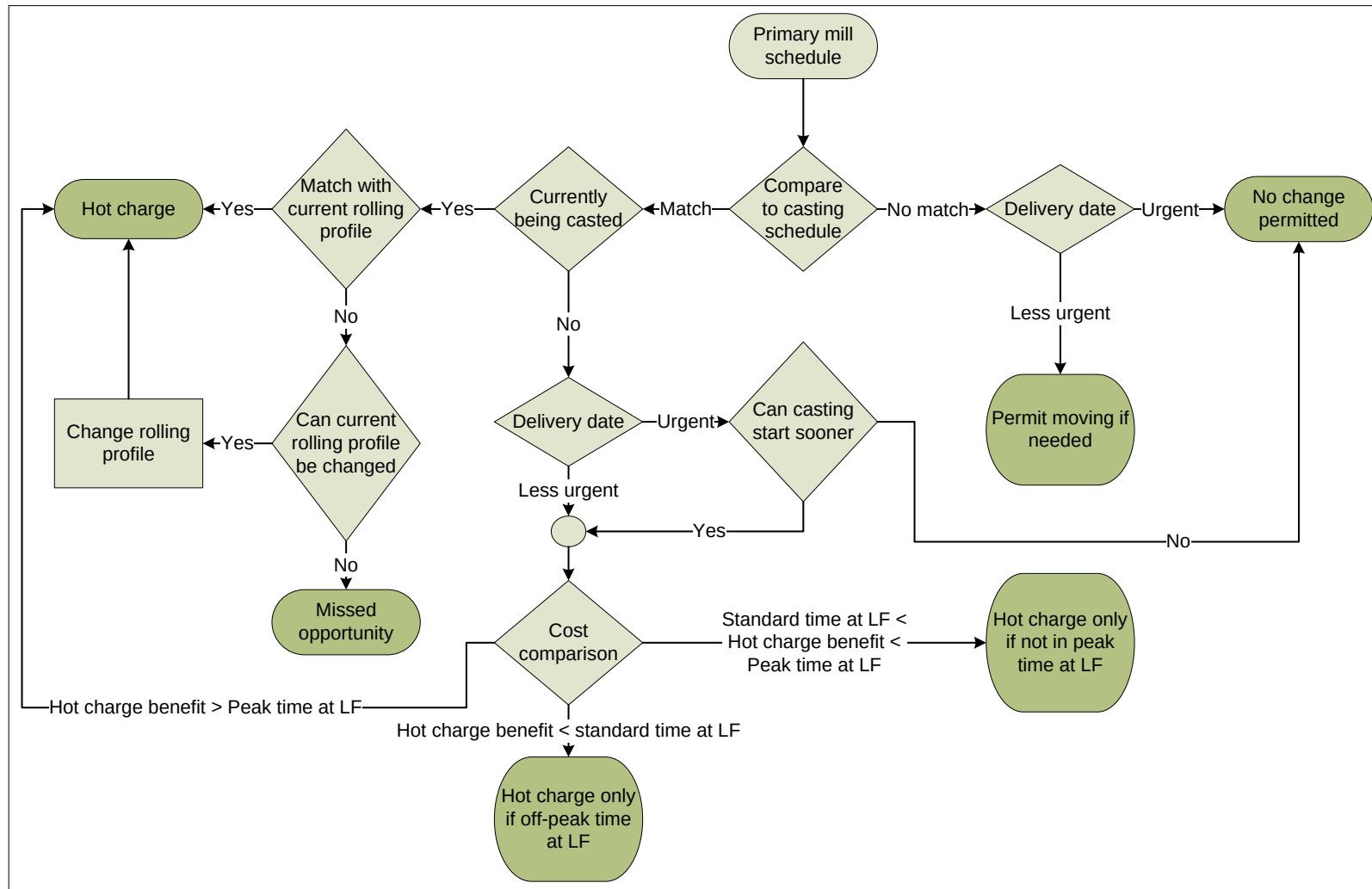


Figure 44: Decision-making flow diagram for the practical integration of initiatives¹¹

¹¹ Ladle furnace is referred to as LF in Figure 44.

Monitor integrated production planning initiatives

The performance of the practical integration of initiatives was also monitored. The practical daily cost benefit of both initiatives is presented in Figure 45. This representation shows the dominance of the hot charging, as expected from the theoretical application (Figure 28 in Section 4.3.6). The total cost benefit achieved by both initiatives using the integrated approach is R3.28 million for the 10 months of implementation.

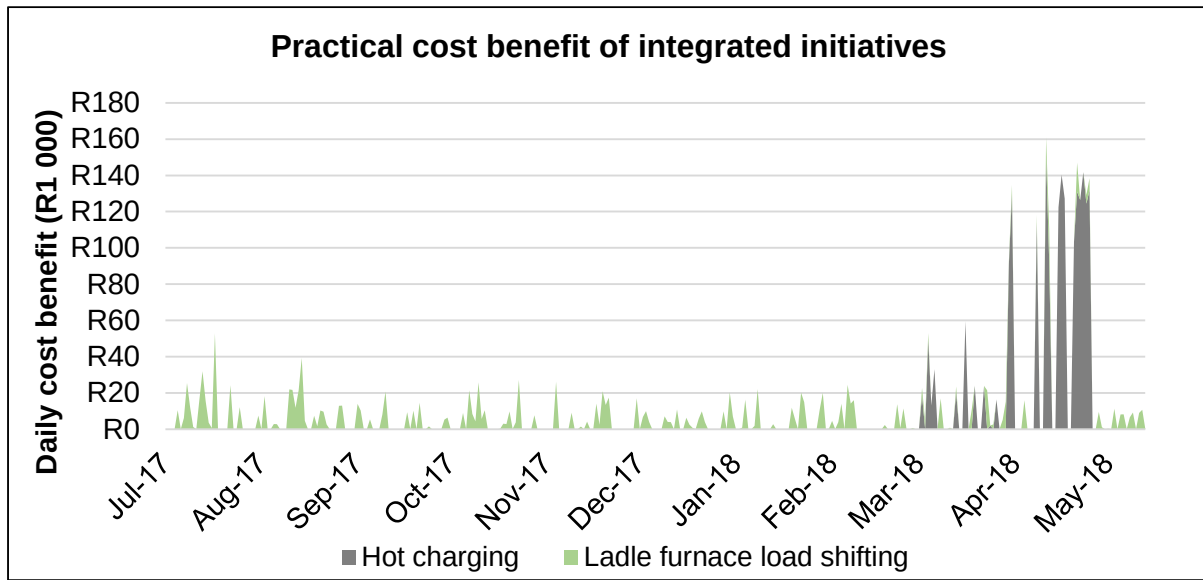


Figure 45: Practical daily cost benefit of integrated initiatives

To illustrate the effect of the integrated approach, ladle furnace load shifting at Plant X was considered separately. Due to the initiative being implemented before the hot charging of the primary rolling mill, it was possible to evaluate the effect on the cost benefit thereof before and after integration. The integration losses were calculated by using the average monthly summer cost benefit prior to integration, and comparing the losses with the actual cost benefits. The integration losses for the practical monthly cost benefit are indicated in Figure 46. The loss due to the integration was calculated as R60 000 for the two months.

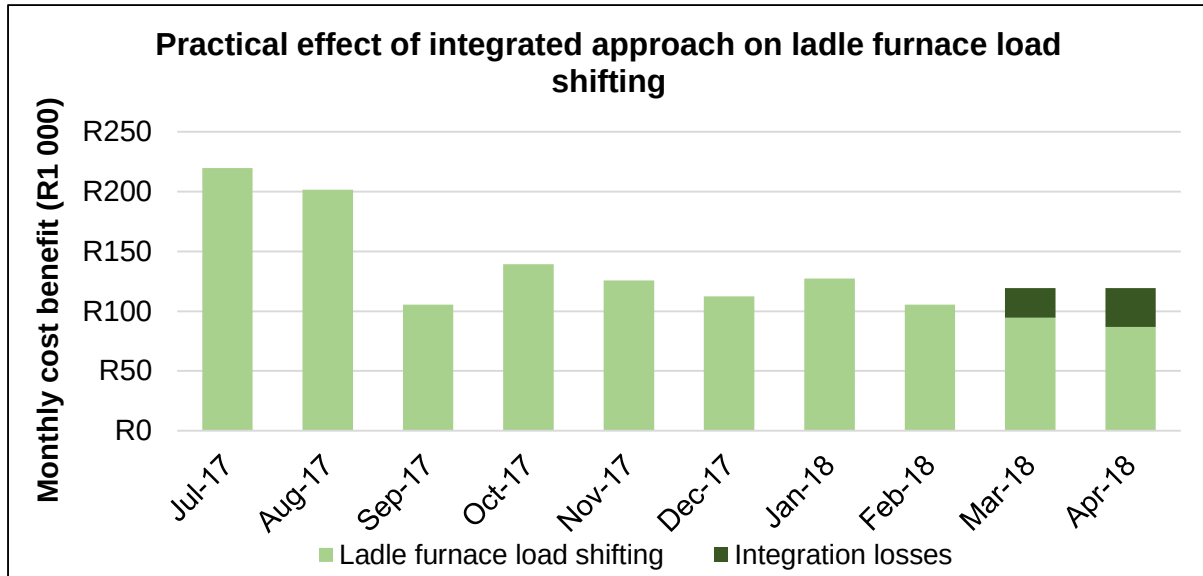


Figure 46: Practical monthly cost benefit of ladle furnace load shifting implementation with compensation for integrated effect

As with the theoretical application, the effect of not using a non-integrated approach was compared with the cost benefit of the integrated approach. This is presented in terms of the practical monthly cost benefit in Figure 47. As with the theoretical application, it was assumed that only ladle furnace load shifting would have been implemented if the option of an integrated approach was not available. Compared with the result in Section 4.3.6 (Figure 29), it is validated that an integrated approach provides a higher cost benefit than a non-integrated approach.

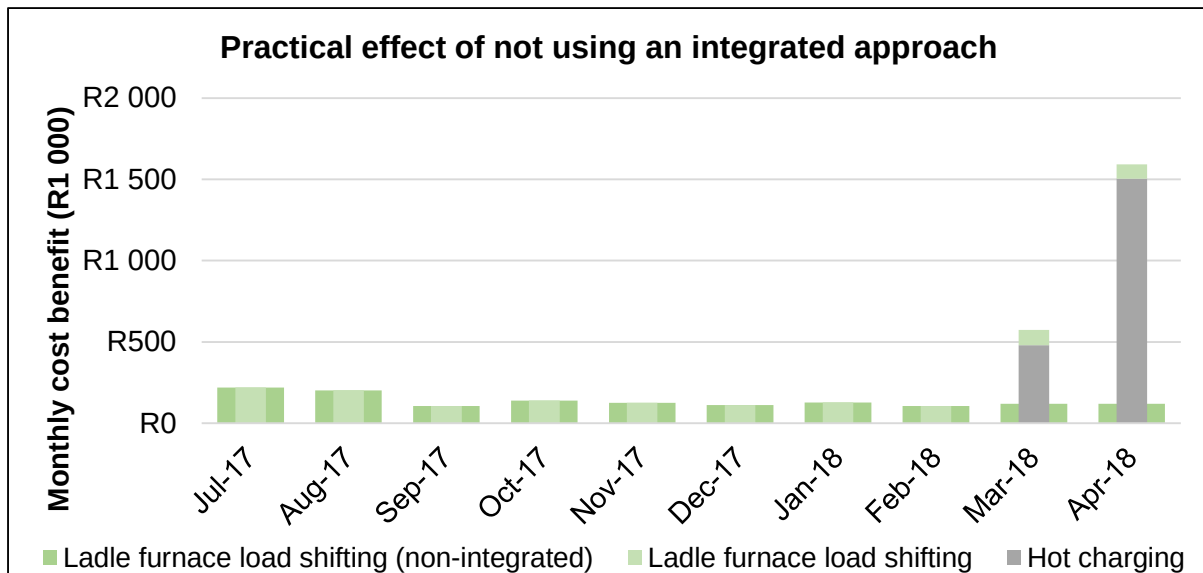


Figure 47: Practical effect of not using an integrated approach

Revise

As with the revision of individual initiatives, the integrated approach was revised regularly by means of feedback discussions with the various involved parties. This made it possible to adapt the approach and refine the integration flow diagram of Figure 44.

5.3. DISCUSSION OF RESULTS

5.3.1. EXTRAPOLATE PRACTICAL RESULTS

The use of a theoretical and practical application on the same facility provides a valuable platform to compare expected results with actual achieved results, and to use these results for recommendations for the study. The theoretical application made it possible to extrapolate the results from the practical application to a full year. The extrapolated practical daily cost benefit of the integrated results is presented in Figure 48.

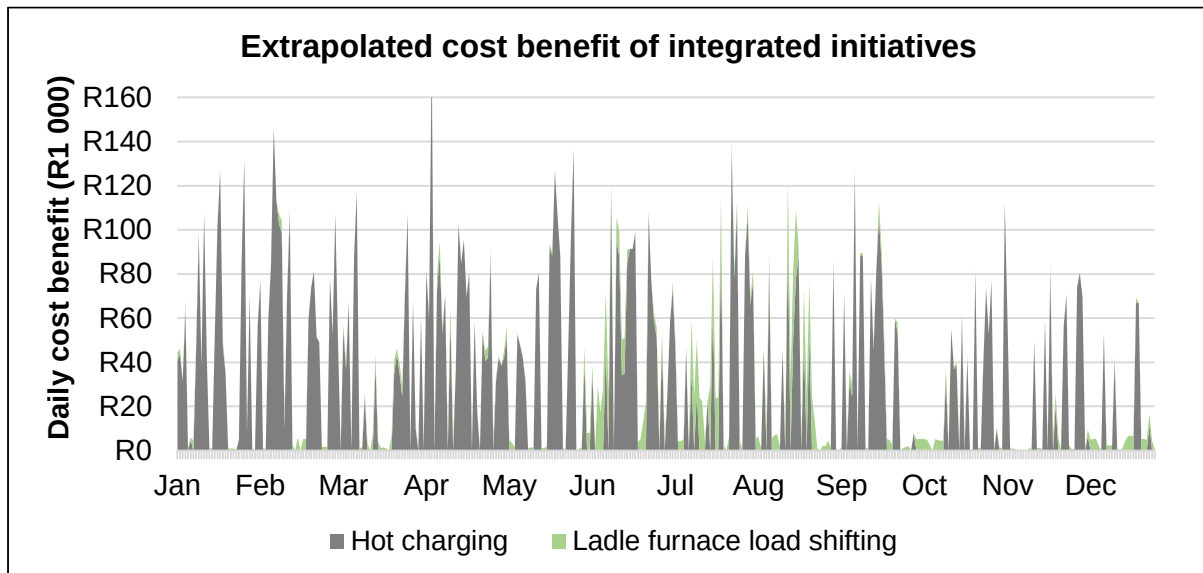


Figure 48: Extrapolated practical daily cost benefit of integrated initiatives

In order to compare the practical annual cost benefit of a non-integrated approach with that of the integrated approach, the cost benefit of the practical non-integrated ladle furnace load shifting initiative was also extrapolated to a one year period. This result is presented in Figure 49.

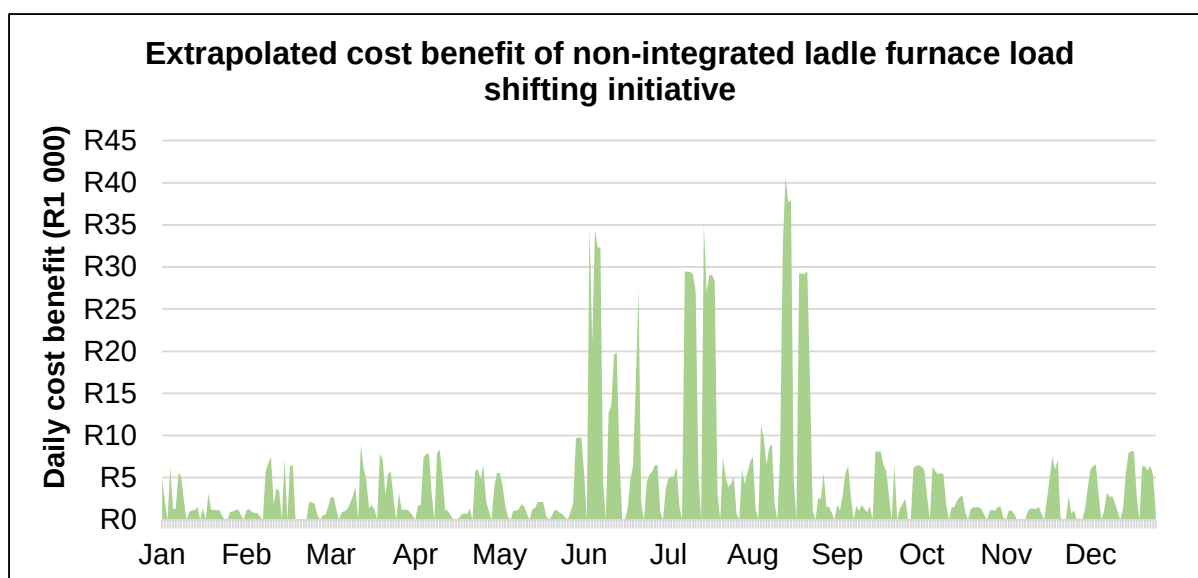


Figure 49: Extrapolated practical daily cost benefit of ladle furnace load shifting

An extrapolated practical monthly cost benefit comparison between the non-integrated and integrated approach is presented in Figure 50. This is considered to be the expected result if the practical integration were to take place for a full year compared with only the ladle furnace load shifting being practically implemented for a full year.

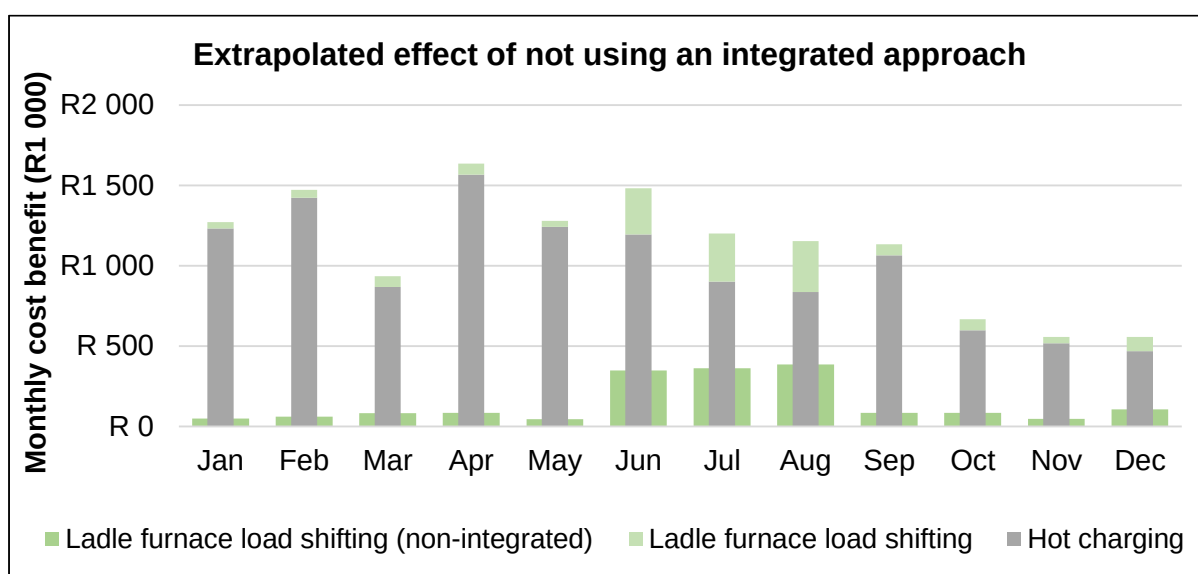


Figure 50: Extrapolated practical effect of not using an integrated approach

An evaluation of the practical yearly cost benefit of the two approaches is presented in Figure 51, using the extrapolated result discussed above. This evaluation shows that if a non-integrated approach was used instead of an integrated approach, only 13% of the annual cost benefit would have been achieved. This serves as a validation of the integrated cost model for steel production planning by the practical application thereof on Plant X.

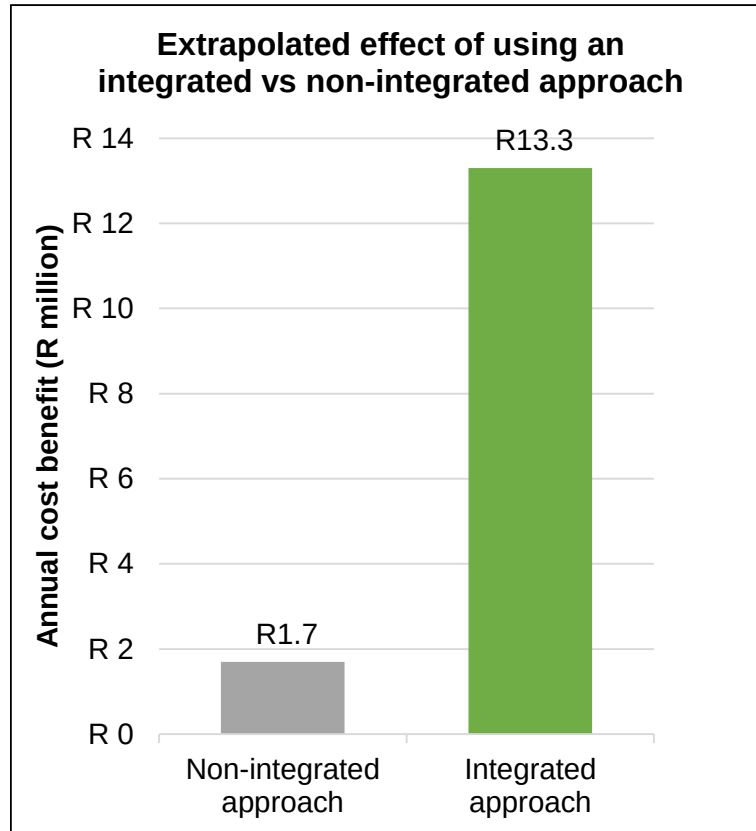


Figure 51: Extrapolated practical yearly cost benefit of integrated initiatives

If the comparison and prioritisation model in Section 5.2.4 provided a higher initiative ranking for hot charging, the non-integrated approach would be expected to consist of the implementation of only the hot charging initiative. The extrapolated practical monthly cost benefit comparison between the non-integrated and integrated approach for this case is presented in Figure 52.

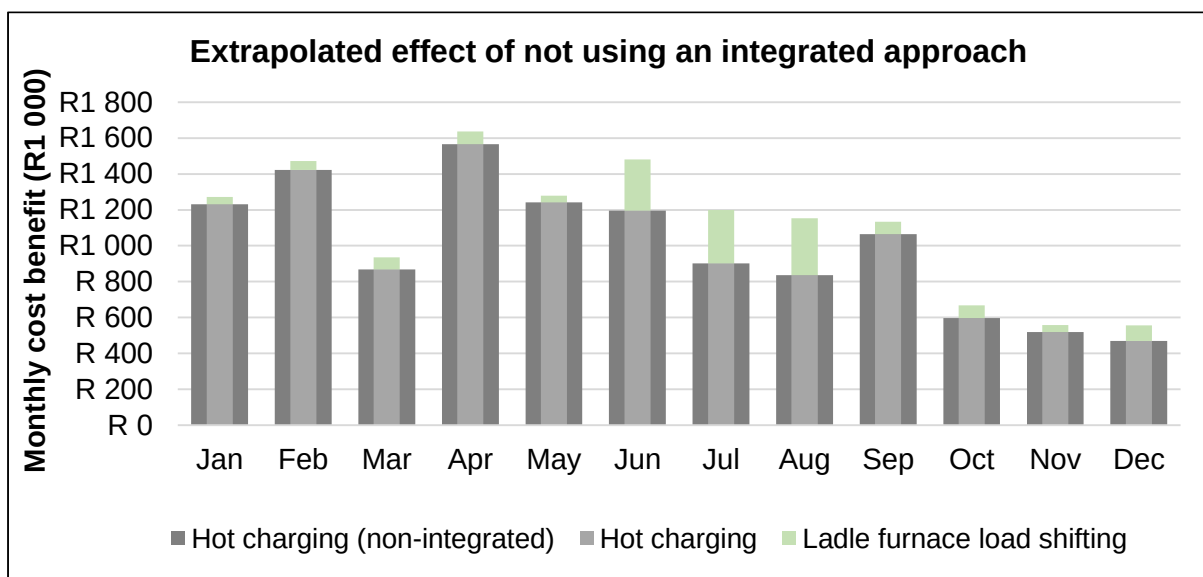


Figure 52: Alternative effect of not using an integrated approach

5.3.2. COMPARE THEORETICAL AND PRACTICAL APPLICATIONS

Using the extrapolated results of the practical application, it is possible to compare it to the theoretical application discussed in Chapter 4. A comparison of the monthly cost benefit for the two applications is presented in Figure 53. From this representation it is observed that the theoretical application provided an accurate estimation of the possible cost benefit on the facility. Minor differences between the cost benefits are observed, which are allocated to the ideal conditions of the theoretical approach, compared with the practical limitations and challenges experienced. These differences will be used to make recommendations for future work when performing such applications.

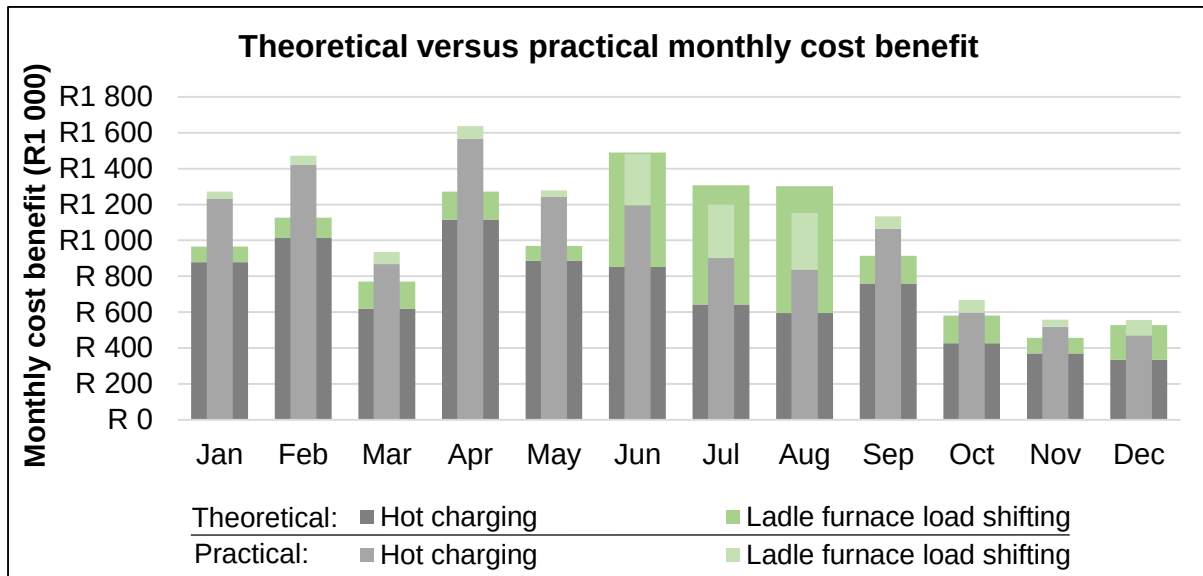


Figure 53: Monthly cost benefits of theoretical and practical applications

The annual cost benefit of the theoretical application is compared with the cost benefit of the extrapolated practical application in Figure 54. This comparison shows that the cost benefit of the extrapolated practical application (R13.3 million) is slightly higher than that of the theoretical application (R11.7 million). The practical application validates the results achieved from the theoretical application, concluding that the methodology reduced the cost of steel production successfully.

The differences between the results achieved by the theoretical and practical applications are allocated to the ideal conditions used when applying the methodology theoretically. The practical challenges experienced proved that actual benefits differ slightly from theoretical benefits. This is, however, addressed by the feedback loop in the methodology.

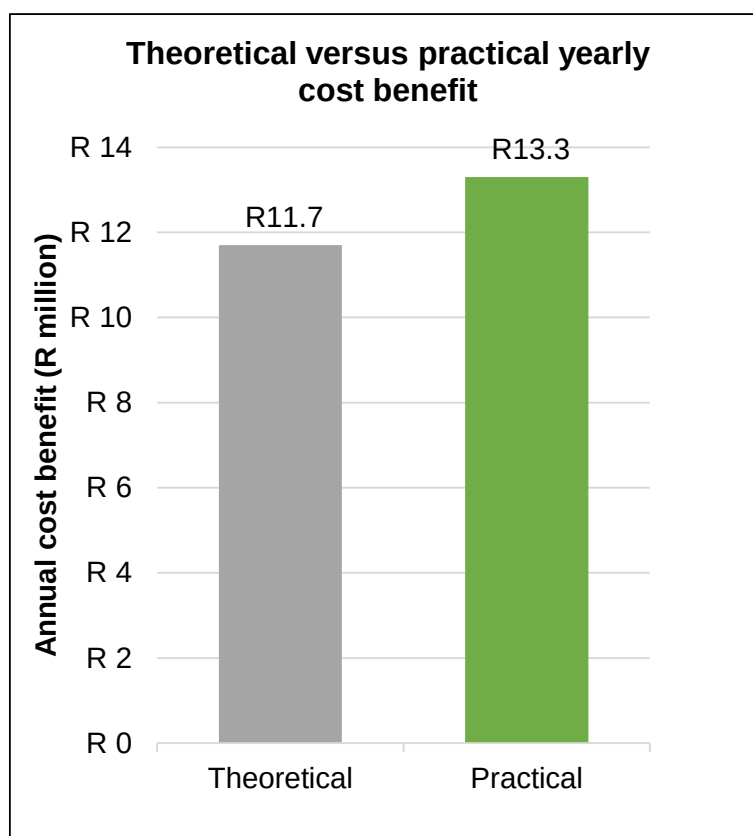


Figure 54: Yearly cost benefits of theoretical and practical applications

5.3.3. POTENTIAL EFFECT ON THE LOCAL STEEL INDUSTRY

The practical result can be further extrapolated to determine the possible effect on the South African steel industry. Plant X produced about 22% of the steel in the South Africa steel market during 2016. The potential effect on this industry is calculated to be R60 million per annum. This validates that an integrated cost model for steel production planning will reduce the cost of steel production in the country if it was implemented on all steelmaking facilities.

The effect of the implemented cost model assisted with production planning and achieved cost savings at Plant X. This was monitored by means of a project-specific baseline, and was approved on a high level and incorporated into the company's key performance indicator reports. These performance indicators focussed specifically on energy cost reduction at the facility. The effect was, however, not yet evaluated as part of the facility's profit margins at the time of publication.

5.4. NOVEL CONTRIBUTIONS OF THE PRACTICAL APPLICATION

As with the previous chapter, the novel contributions of this chapter are revisited with reference to the contributions listed and discussed in Section 1.4.

Contribution 1:

*Development of a **new cost model** for steel production planning by **adapting and combining multiple** industry applied methods*

The practical application adapted the existing initiatives for Plant X as part of the implementation. Detailed discussions of the implementation tools used for adapting the initiative were presented, proving that initiatives can be adapted for a specific facility. The adaption of initiatives was conducted by using the *plan* step of ISO 50001, and the practically achieved results confirm the validity of the approach in the methodology. The integration of the existing methods used to develop the methodology was also validated in this practical application. The extrapolated cost benefit of R13.3 million per annum validates the integrated approach that was used.

Contribution 2:

*A **unique approach** for the **dynamic prioritisation** of multiple implemented initiatives*

Integration of the implemented initiatives was achieved by using the dynamic prioritisation techniques presented in the methodology to develop a practical integration flow diagram. The dynamic prioritisation was incorporated into the implementation tools that were developed, and used the accurate benefit quantification of individual initiatives. The extrapolated practical result was similar to the expected result from the theoretical application, which validates the practical use of the approach developed in the methodology.

Contribution 3:

*A **uniquely adopted solution** to address **personnel-related resistance** towards automated solutions at marginally profitable facilities*

Identified initiatives were adapted for the practical application at Plant X, using the adapted tools as part of the methodology. The achieved cost benefit of the practical application on Plant X thus validates the use thereof on a marginally profitable facility. ISO 50001-based implementation strategies were adopted in the solution to address the unique conditions of such facilities. The extrapolation of the result indicating a potential annual cost benefit of R60 million per annum validates the use of the methodology in these unique conditions.

Contribution 4:

Novel integrated model for cost-efficient steel production planning

The practical application of the methodology at Plant X served as a validation of the developed integrated cost model for steel production planning. It was thereby confirmed that the novel integrated model successfully resulted in cost reductions on a steelmaking facility. Two of the originally identified initiatives were practically implemented at Plant X. By extrapolating the results it was found that the use of a non-integrated approach would have only provided 13% of the practical cost benefit. A further extrapolation to the South African steel industry indicated that the implementation of the integrated cost model for steel production planning will have an annual cost benefit of R60 million.

5.5. CONCLUSION

This chapter of the thesis validates that the integrated cost model for steel production planning developed in Chapter 3 reduces the cost of steel production. This validation was achieved by the practical application of the integrated cost model at Plant X. The application of the steps of the methodology was discussed in detail, with some of the groundwork from the theoretical application in Chapter 4 being used. The main focus of this chapter was the implementation step as based on the PDCA approach of ISO 50001. Two of the originally identified initiatives were applied practically to Plant X, and the practical results were extrapolated to an annual cost benefit using the theoretical application results.

The extrapolated practical results indicated that a cost benefit of R13.3 million could be achieved by using the developed integrated cost model, compared with the cost benefit of R1.7 million when using a non-integrated approach. The theoretical and practical applications were compared, providing a valuable platform for recommendations for future work. From this comparison it was found that the results of the practical application are similar to that of the theoretical application, thereby validating the practical use of the methodology on an actual steelmaking facility. The extrapolation of the practical results further indicated a potential cost benefit of R60 million per annum for the South African steelmaking industry.

Chapter 6: Conclusion

The last chapter serves as a conclusion to the study. The research objectives and novel contributions are evaluated. An overview and recommendations for future work is provided.

6. CONCLUSION AND RECOMMENDATIONS

6.1. PREAMBLE

This chapter serves as the conclusion of the thesis. An overview of the study is discussed, which provides a short summary of the problem that was identified and how it was addressed by the developed solution. The research objectives are reviewed along with the formulated novel contributions to indicate how they were achieved. Lastly, recommendations are given for future work related to the research of this thesis.

6.2. OVERVIEW OF THE STUDY

The problem that was identified from the background is that the South African steel industry is facing financial challenges along with the rest of the world's steel producers. A need was identified to reduce the cost of steel production. Energy cost was highlighted as a large contributor to steel production cost, and it was decided to mainly focus on reducing these costs on steelmaking facilities. Specific focus was placed on steel production planning to achieve these results.

Existing research on production planning in various industries were reviewed, emphasising the lack of an integrated steel production planning model, and applications thereof in South Africa. This problem was addressed by developing a new integrated cost model for steel production planning. Four novel contributions were formulated from this model. The main focus of the study was on adapting and integrating existing industry applied methods and initiatives to construct a new cost model for steel production planning. The development of the study focused on the integration of the following fields:

- Existing energy management methods;
- Steel production planning energy cost saving initiatives;
- Steelmaking facility sections;
- Different energy sources; and
- Energy and production benefits.

The integrated cost model consists of five main steps, which were all expanded into more detail. The concept of the cost model is to identify, evaluate, compare and prioritise, implement, and integrate energy cost saving initiatives focused on steel production planning. The focus on production planning ensures that minimum capital is required as most of the initiatives incorporate operational improvements. The solution did not focus on automated solutions because of the capital restrictions and resistant personnel in the constrained market

and the focus on marginally profitable facilities. During the development of the methodology, five potential initiatives were evaluated for implementation on steel production planning.

The methodology was verified by the theoretical application thereof on a case study facility (referred to as Plant X) in Chapter 4. The theoretical application used data for a full year, and theoretically assessed each step of the methodology by applying it to the data set. During this application, the identified initiatives were critically evaluated, and it was found that four of the initiatives are feasible for implementation on Plant X. The theoretical implementation was conducted by assessing the potential benefits of each initiative, and dynamically prioritising these initiatives based on their benefits. The integration mainly consisted of the dynamic prioritisation while considering restricting effects that initiatives have on one other.

The potential benefit of implementing the integrated cost model for a year was calculated as R11.9 million. It was determined that the use of a non-integrated approach would have only resulted in 29% of the potential cost benefits. The methodology was thereafter validated by the practical application thereof in Chapter 5. This application led to the practical implementation and integration of two of the identified initiatives on the facility.

The practical application focused on the causality of the achieved cost benefit by discussing how the initiatives were practically implemented and integrated on Plant X. The results of the practical application was extrapolated to a full year by using the results of the theoretical application. The extrapolated results indicated that the integrated cost model would result in cost benefits of R13.3 million at Plant X if it was implemented for a full year. It was further determined that a non-integrated approach would have only resulted in 13% of the cost benefit.

Further extrapolation to the South African steel industry indicated that the application of the integrated cost model would have an impact of R60 million per annum if implemented on all of the facilities in the country. It was validated that the need for the study was addressed by the developed solution. The use of the integrated cost model does reduce the cost of steel production.

6.3. EVALUATION OF THE NOVEL CONTRIBUTIONS

The research objectives of the study were listed in Section 1.3.3, and were addressed as listed below:

- Existing initiatives and generic methods were assessed, adapted, and combined;
- The theoretical value of possible solutions were evaluated;
- Integrated initiatives were compared and prioritised;

- The cost of steel production was reduced using minimum capital;
- An integrated approach was developed for the solution; and
- The integrated cost model was practically implemented on steel production planning.

The novel contributions of the study were formulated from these research objectives and were listed and discussed in Section 1.4. The novel contributions were discussed at the hand of the methodology, verification and validation at the end of each relevant chapter. The relevance of the study to each of the novel contributions is provided in this section.

Contribution 1:

*Development of a **new cost model** for steel production planning by **adapting and combining multiple** industry applied methods*

An extensive review of existing solutions in various industries not only led to the identification of the need for the study, but also served as a valuable database for constructing the solution. The existing industry applied methods and initiatives were adapted to be relevant to steel production planning, and were used for the development and application of the new cost model for steel production planning. A large focus of the study was on the integration of several important aspects, including the adapting and combining of existing research to develop the new cost model.

Contribution 2:

*A **unique approach** for the **dynamic prioritisation** of multiple implemented initiatives*

The identified initiatives were critically evaluated from historical data to determine the potential benefits and how they can be utilised. Practical constraints were used to evaluate restrictions for the implementation of initiatives, and their interactive effects on one another. These factors were used in the dynamic prioritisation of implemented initiatives, and realised cost benefits from more than one initiative at a time. This dynamic prioritisation introduced a unique approach towards using historical data and quantifying benefits. The use of dynamic prioritisation enabled the practical implementation of two simultaneous initiatives on Plant X, rather than only implementing one initiative. It was indicated from the results that a non-integrated solution would have only results in 13% of the cost benefits.

Contribution 3:

A uniquely adopted solution to address personnel-related resistance towards automated solutions at marginally profitable facilities

The developed integrated cost model was theoretically and practically applied to a South African facility, namely, Plant X. The development of the solution was aimed at the restricting conditions of marginally profitable facilities, such as a shortage of capital as well as resistance from plant personnel due to strained market conditions. The personnel-related resistance was addressed by uniquely adopting an ISO 50001-based implementation strategy rather than using automated solutions. The cost model was also practically implemented on Plant X, resulting in an annual cost benefit of 13.6 million.

Contribution 4:

Novel integrated model for cost-efficient steel production planning

The study focused on developing and implementing a novel integrated cost model for steel production planning. The cost model was developed by assessing, adapting and integrating existing solutions into a single methodology. The basic steps in the methodology focused on the identification, evaluation, comparison and prioritisation, implementation, and integration of production planning initiatives. The theoretical and practical application of the methodology on Plant X proved the validity of the solution to solve the identified problem. The extrapolation of the achieved results to the South African steel industry indicated a potential benefit of R60 million per annum. The new integrated cost model will therefore be effective in improving the cost efficiency of steel production, and resultantly addressing the identified problem.

6.4. RECOMMENDATIONS FOR FUTURE WORK

6.4.1. FURTHER APPLICATIONS

During the development and application of the integrated cost model, a few recommendations for future work were identified. The first recommendation is to apply the integrated cost model on the remainder of the steel-manufacturing facilities in South Africa. The results were extrapolated to the rest of the steel industry in the country, and it would be beneficial to practically achieve these potential benefits. It would also serve as a further validation of the methodology.

It is secondly recommended that the integrated cost model be implemented on steel-manufacturing facilities in other countries with marginally profitable steelmaking facilities. The

methodology can also be adapted for use on more successful steelmaking facilities. The unique conditions of marginally profitable facilities placed several restrictions on the development of the new cost model. It should, however, be possible to adapt the integrated cost model to use automated solutions for facilities where there is less resistance towards such solutions. The methodology is expected to have a similar or improved result when using an automated approach for the implementation of initiatives.

Thirdly, it is recommended to adapt the methodology to be applicable to other industries using similar production planning functions. Even though the methodology was developed for the application thereof on steelmaking facilities, it will be possible to adapt it to other production lines. This will lead to cost savings in other industries using the unique integrated approach.

6.4.2. MODIFICATIONS TO THE APPROACH

A few recommendations for the developed approach were identified. The use of a theoretical and practical application on Plant X made it possible to compare the potential and actual benefits on the facility. The comparison showed that the primary rolling mill furnace initiative achieved higher practical benefits than expected, and the ladle furnace load shifting achieved lower benefits. This is assigned to differences between the theoretical benefit quantification methods and baseline methodologies that were used.

The practical constraints of the initiatives could also have affected the performance of these initiatives. It was found that the ladle furnace load shifting opportunities are more difficult to use than those of the increased hot charging initiative. It is recommended to further increase the importance of practical constraints in the initial prioritisation of initiatives to be implemented (Step 3 of the methodology). This affected the order in which initiatives were implemented, which led to a higher total cost benefit by first implementing the increased hot charging initiative. This would have also prioritised the hot charging benefit for the non-integrated approach. The benefit for only this solution would, however, still have been lower than that of the integrated approach.

It is further recommended that the theoretical cost benefits and practical constraints used by the dynamic prioritisation model be updated regularly based on the latest data and information. This will ensure that the actual performance of initiatives are considered for the dynamic prioritisation. Therefore, it will be possible to update the prioritisation if an initiative results in lower or higher cost benefits than originally expected, or if the practical constraints are more or less difficult to address.

The last recommendation is to implement the initiatives separately before proceeding with the integrated implementation (i.e. stop the implementation of an initiative when implementing

another initiative). This would not have been beneficial from a cost benefit point of view, but would have provided more insight for the assessment of the integrated cost model. Inputs from such an assessment would have provided valuable feedback for the dynamic prioritisation model to be further optimised.

6.5. CLOSURE

A need was identified to reduce the cost of steel production. Energy cost was highlighted as a significant contributor to steel production costs. It was decided to focus on production planning on a steelmaking facility, which led to the development of a new integrated cost model for steel production planning. The use of an integrated approach was required to ensure that benefits could be achieved from multiple initiatives, rather than only focusing on a single initiative. The cost model was developed by adapting and integrating existing solutions and initiatives into a single methodology.

The integrated cost model was theoretically and practically applied to a marginally profitable case study facility. The theoretical application verified the use of the methodology by a detailed evaluation of five identified initiatives on the facility. The practical application served as a validation of the methodology with the application of two initiatives on the facility. An extrapolation of the practical results indicated a potential cost reduction of R60 million per annum for the South African steelmaking industry. It was resultantly demonstrated that the integrated cost model for steel production planning is able to reduce the cost of steel production. Therefore, the developed methodology addresses the identified need for the study.

REFERENCES

- [1] W. J. Breytenbach, H. G. Brand and J. H. Marais, "Framework for operational changes to reduce electricity costs in the South African steel industry," in *The 14th International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2017.
- [2] S. G. Van Niekerk, W. J. Breytenbach and J. H. Marais, "Developing an optimisation model for industrial furnace gaseous fuel distribution for energy cost savings," in *The 14th International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2017.
- [3] G. H. Popescu, E. Nica, R. O. Stefanescu-Mihaela and G. Lazaroiu, "The United States (US) steel import crises and the global production overcapacity till 2016," *Metalurgija*, vol. 3, no. 55, p. 538–540, 2016.
- [4] International Trade Administration Commission of South Africa, "Monitoring and analysis of South African steel imports," *Trade Monitor*, September 2016.
- [5] World Steel Association, "World steel in figures 2017," worldsteel.org, Beijing, 2017.
- [6] S. Roberts and N. Zalk, "Addressing market power in a small, isolated, resource-based economy: the case of steel in South Africa," in *The Centre on Regulation and Competition 3rd International Conference*, Cape Town, 2004.
- [7] Merchantec Research, "Industry challenges and opportunities (ferrous metals downstream sector)," Department of Trade and Industry & Industrial Development Corporation, 2015.
- [8] 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. 4, p. 1–13, 2017.
- [9] L. Tang, J. Liu, A. Rong and Z. Yang, "A multiple traveling salesman problem model for hot rolling scheduling in Shanghai Baoshan Iron & Steel Complex," *European Journal of Operational Research*, vol. 124, p. 267–282, 2000.
- [10] L. Van Dyk, "A census of South African industrial engineers, based on data extracted from LinkedIn," in *SAIIE26 Proceedings*, Muldersdrift, 2014.

- [11] ArcelorMittal South Africa, "Capacity for ArcelorMittal South Africa plants," *ArcelorMittal South Africa Factor Report*, p. 14–15, May 2016.
- [12] Deloitte, "The economic impact of electricity price increases on various sectors of the South African economy: A consolidated view based on the findings of existing research," Johannesburg, 2012, Deloitte.
- [13] M. Kohler, "The economic impact of rising energy prices: A constraint on South Africa's growth and poverty reduction opportunities," in *TIPS Forum*, Johannesburg, 2006.
- [14] K. He and L. Wang, "A review of energy use and energy-efficient technologies for the iron and steel industry," *Renewable and Sustainable Energy Reviews*, vol. 70, p. 1022–1039, 2017.
- [15] World Steel Association, "Fact sheet: Energy use in the steel industry," worldsteel.org, Beijing, 2018.
- [16] Asia Pacific Partnership for Clean Development and Climate, The State-of-the-Art Clean Technologies (SOACT) for Steelmaking Handbook, 2nd ed., Berkeley, CA: Lawrence Berkeley National Laboratory and Washington, DC: American Iron and Steel Institute, 2010.
- [17] World Steel Association, "Energy intensity project report and energy intensity system," worldsteel.org, Beijing, 2014.
- [18] M. Rager, C. Gahm and F. Denz, "Energy-oriented scheduling based on evolutionary algorithms," *Computers & Operations Research*, vol. 54, p. 218–231, 2015.
- [19] E. W. T. Ngai, C. K. M. To, V. S. M. Ching, L. K. Chan, M. C. M. Lee, Y. S. Choi and P. Y. F. Chai, "Development of the conceptual model of energy and utility management in textile processing: A soft system approach," *International Journal of Production Economics*, vol. 135, p. 607–617, 2012.
- [20] K. Fang, N. Uhan, F. Zhao and J. W. Sutherland, "A new approach to scheduling in manufacturing for power consumption and carbon footprint reduction," *Journal of Manufacturing Systems*, vol. 30, p. 234–240, 2011.
- [21] L. Merkert, I. Harjunkoski, A. Isaksson, S. Saynevirta, A. Saarela and G. Sand, "Scheduling and energy: Industrial challenges and opportunities," *Computers & Chemical Engineering*, vol. 72, p. 183–198, 2015.

- [22] K. Biel and C. H. Glock, "Systematic literature review of decision support models for energy-efficient production planning," *Computers & Industrial Engineering*, vol. 101, p. 243–259, 2016.
- [23] J. Lin, M. Liu, J. Hao and S. Jiang, "A multi-objective optimization approach for integrated production planning under interval uncertainties in the steel industry," *Computers & Operations Research*, vol. 72, pp. 189-203, 2016.
- [24] W. J. Breytenbach, "Framework for operational changes to reduce electricity costs in the South African steel industry," PhD thesis, Faculty of Engineering, North-West University, Potchefstroom, 2017.
- [25] Department of Trade and Industry, "Introduction and implementation of an energy management system and energy systems optimization," Department of Trade and Industry, Pretoria, 2011.
- [26] R. Remus, M. A. Monsonet, S. Roudier and L. D. Sancho, "Best available techniques (BAT) reference document for iron and steel production," European Commission JRC Reference Report, Seville, Spain, 2013.
- [27] X. Shen, L. Chen, S. Xia, Z. Xie and X. Qin, "Burdening proportion and new energy-saving technologies analysis and optimization for iron and steel production system," *Journal of Cleaner Production*, vol. 172, p. 2153–2166, 2018.
- [28] E. Worrel, P. Blinde, M. Neelis, E. Blomen and E. Masanet, "Energy efficiency improvement and cost saving opportunities for the US iron and steel industry: An ENERGY STAR guide for energy and plant managers," Energy Analysis Department, Environmental Energy Technologies Division, University of California, Berkeley, CA, 2010.
- [29] Q.-K. Pan, Q.-D. Chen, T. Meng, B. Wang and L. Gao, "A mathematical model and two-stage heuristic for hot rolling scheduling in compact strip production," *Applied Mathematical Modelling*, vol. 48, p. 516–533, 2017.
- [30] S.-L. Jiang, M. Liu, J.-H. Lin and H.-X. Zhong, "A prediction-based online soft scheduling algorithm for the real-world steelmaking-continuous casting production," *Knowledge-Based Systems*, vol. 111, p. 159–172, 2016.

- [31] M. H. Fazel Zarandi and P. Ahmadpour, "Fuzzy agent-based expert system for steel making process," *Expert Systems with Applications*, vol. 36, p. 9539–9547, 2009.
- [32] B. Karwat, "Optimization of production schedules in the steel production system," *Archives of Civil and Mechanical Engineering*, vol. 12, p. 240–252, 2012.
- [33] 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 and Steelmaking*, vol. 40, no. 1, p. 74–80, 2013.
- [34] Z. Dao-fei, Z. Zhong and G. Xiao-qiang, "Intelligent optimization-based production planning and simulation analysis for steelmaking and continuous casting process," *Journal of Iron and Steel Research*, vol. 17, p. 19–24, 2010.
- [35] I. Mattik, P. Amorim and H.-O. Gunther, "Hierarchical scheduling of continuous casters and hot strip mills in the steel industry: a block planning application," *International Journal of Production Research*, vol. 52, no. 9, p. 2576–2591, 2014.
- [36] New Energy and Industrial Technology Development Organization (NEDO), "Global warming countermeasures: Japanese Technologies for energy savings/GHG emission reduction (2008 revised edition)," Kyoto Mechanisms Promotion Department, NEDO, Kawasaki, 2008.
- [37] PSI Software for Utilities and Industry, "Totally integrated planning at Isdemir: Hot savings with hot charging," PSI Software for Utilities and Industry, [Online]. Available: <http://www.psi.de/en/psi-productionmanagement/magazin/hot-savings-with-hot-charging/>. [Accessed 29 April 2018].
- [38] C. Xu, G. Sand, I. Harjunoski and S. Engell, "A new heuristic for plant-wide schedule coordination problems: The intersection coordination heuristic," *Computers & Chemical Engineering*, vol. 42, p. 152–167, 2012.
- [39] C. Gahm, F. Denz, M. Dirr and A. Tuma, "Energy-efficient scheduling in manufacturing companies: A review and research framework," *European Journal of Operational Research*, vol. 248, p. 744–757, 2015.
- [40] X. Gong, T. De Pessemer, W. Joseph and L. Martens, "An energy-cost-aware scheduling methodology for sustainable manufacturing," in *The 22nd CIRP conference on Life Cycle Engineering*, Cape Town, 2015.

- [41] H. Hadera, I. Harjunoski, G. Sand, I. E. Grossmann and S. Engell, "Optimization of steel production scheduling with complex time-sensitive electricity cost," *Computers & Chemical Engineering*, vol. 76, p. 117–136, 2015.
- [42] W. Hamer, "Analysing electricity cost saving opportunities on South African gold processing plants," MEng dissertation, Faculty of Engineering, North-West University, Potchefstroom, 2014.
- [43] 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, p. 174–183, 2017.
- [44] R. Maneschiijn, "The development of a system to optimise production costs around complex electricity tariffs," MEng dissertation, Faculty of Engineering, North-West University, Potchefstroom, 2012.
- [45] K. Nolde and M. Morari, "Electrical load tracking scheduling of a steel plant," *Computers & Chemical Engineering*, vol. 34, p. 1899–1903, 2010.
- [46] J. A. Swanepoel, E. H. Mathews, J. Vosloo and L. Liebenberg, "Integrated energy optimisation for the cement industry: A case study perspective," *Energy Conversion and Management*, vol. 78, p. 765–775, 2014.
- [47] T. Yuan-yuan, H. Ying-lei and L. Shi-xin, "Two-stage mathematical programming approach for steelmaking process scheduling under variable electricity price," *Journal of Iron and Steel Research, International*, vol. 20, no. 7, p. 1–8, 2013.
- [48] M. Biondi, G. Sand and I. Harjunoski, "Optimization of multipurpose process plant operations: A multi-time-scale maintenance and production scheduling approach," *Computers & Chemical Engineering*, vol. 99, p. 325–339, 2017.
- [49] W. Liu, L. Sun, J. Ding and T. Chai, "Study on ladle schedule of steel making process using heuristic scheduling algorithm," in *Proceedings of the 18th World Congress*, Milano, 2011.
- [50] M. Lochmüller and G. Schembecker, "Simultaneous optimization of scheduling, equipment dimensions and operating conditions of sequential multi-purpose batch plants," *Computers & Chemical Engineering*, vol. 94, p. 157–179, 2016.

- [51] J.-Y. Long, Z. Zheng, X.-Q. Gao and Y.-M. Gong, "Production planning system for the whole steelmaking process of Panzhihua Iron and Steel Corporation," *Journal of Iron and Steel Research, International*, vol. 21, p. 44–50, 2014.
- [52] M. E. Moshidi, "An analysis of effective maintenance planning at a steel manufacturer," MBA mini-dissertation, School of Business & Governance, North-West University, Potchefstroom, 2014.
- [53] 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*, Milano, 2011.
- [54] B. David, Y. Goldblatt and Y. Zhang, "Industrial experiences in maximizing profit of steel production," in *6th International Congress on the Science & Technology of Steelmaking (ICS 2015)*, Beijing, 2015.
- [55] L. S. Dias and G. I. Marianthi, "Integration of scheduling and control under uncertainties: Review and challenges," *Chemical Engineering Research and Design*, vol. 116, p. 98–113, 2016.
- [56] D. Gajic, H. Hadera, L. Onofri, I. Harjunkski and S. Di Gennaro, "Implementation of an integrated production and electricity optimization system in melt shop," *Journal of Cleaner Production*, vol. 155, p. 39–46, 2017.
- [57] Z. Li and M. G. Ierapetritou, "Integrated production planning and scheduling using a decomposition framework," *Chemical Engineering Science*, vol. 64, no. 16, p. 3585–3597, 2009.
- [58] J. H. Marais, "An integrated approach to optimise energy consumption of mine compressed air systems," PhD thesis, Faculty of Engineering, North-West University, Potchefstroom, 2012.
- [59] N. K. Shah and M. G. Ierapetritou, "Integrated production planning and scheduling optimization of multisite, multiproduct process industry," *Computers & Chemical Engineering*, vol. 37, p. 214–226, 2012.
- [60] S. Zhao, I. E. Grossmann and L. Tang, "Integrated scheduling of rolling sector in steel production with consideration of energy consumption under time-of-use electricity prices," *Computers & Chemical Engineering*, vol. 11, p. 55–65, 2018.

- [61] N. Jordaan, "New demand side management opportunities in the precious metal industry," PhD thesis, Faculty of Engineering, North-West University, Pretoria, 2007.
- [62] B. Matthews and I. K. Craig, "Demand side management of a run-of-mine ore milling circuit," *Control Engineering Practice*, vol. 21, p. 759–768, 2013.
- [63] A. R. Adams and D. Petrarolo, "Reducing inventory holding costs for consumable items in large steelworks," *South African Journal of Industrial Engineering*, vol. 12, no. 2, p. 1–11, 1993.
- [64] P. K. Pretorius and J. K. Visser, "Investigation of the maintenance organisation for hot rolling mills," *South African Journal of Industrial Engineering*, vol. 12, no. 2, pp. 25-38, 2001.
- [65] Z. Mpanza, D. Nyembwe and H. Nel, "Investigating the impact of poor utilisation of quality management system in a South African foundry," in *SAIIE25 Proceedings*, Stellenbosch, 2013.
- [66] L. Mufamadi and T. S. Hattingh, "The application of the PDSA cycle to solve production challenges at the electric-arc furnace," in *SAIIE25 Proceedings*, Stellenbosch, 2013.
- [67] D. Hartmann, T. M. Malaba and C. Saasa, "Exploring the need for planned maintenance in response to low productivity at a heavy steel manufacturer," in *SAIIE26 Proceedings*, Muldersdrift, 2014.
- [68] L. Tang, J. Liu, A. Rong and Z. Yang, "A review of planning and scheduling systems and methods for integrated steel production," *European Journal of Operational Research*, vol. 133, p. 1–20, 2001.
- [69] T. Aouam and N. Brahimi, "Integrated production planning and order acceptance under uncertainty: A robust optimization approach," *European Journal of Operational Research*, vol. 228, p. 504–515, 2013.
- [70] P. Cowling and W. Rezig, "Integration of continuous caster and hot strip mill planning for steel production," *Journal of Scheduling*, vol. 3, no. 4, 2000.
- [71] Z. LV, J. Xu, Z. Xuejun and F. Haitao, "Research and application of an intelligent integrated planning and scheduling system," in *Global Congress on Intelligent Systems*, Xiamen, 2009.

- [72] N. Tu, H. Huang, T. Ma, B. Zheng and T. Chai, "Model and algorithm of integrated lot planning for steelmaking-continuous casting-hot rolling," in *The Control and Decision Conference*, Guilin, 2009.
- [73] B.-L. Zhu, H.-B. Yu and X.-Y. Huang, "Research approaches on integrated planning for iron and steel enterprises," in *The IEEE International Conference on Systems, Man and Cybernetics*, Taipei, 2006.
- [74] B.-L. Zhu, H.-B. Yu and X.-Y. Huang, "An improved method for integrated planning model of iron and steel," in *The International Conference on Intelligent Computation Technology and Automation (ICICTA)*, Changsha, 2010.
- [75] J. Lin, H. Jinghua, L. Min and J. Shenglong, "An integrated planning approach based on harmony search algorithm and prediction model for steelmaking-continuous casting-hot rolling process," in *11th World Congress on Intelligent Control and Automation (WCICA)*, Shenyang, 2014.
- [76] J. P. Birat and H. Laveline, "Steel production & smart electricity grids," European Steel Technology Platform, Paris, 2014.
- [77] S. Ashok, "PLC-based load management in steel rolling mills," *Energy Engineering*, vol. 107, no. 4, p. 38–53, 2010.
- [78] S. J. Stoddard, "Project process mapping: Evaluation, selection, implementation, and assessment of energy cost reduction opportunities in manufacturing," MBA and MSc thesis, Massachusetts Institute of Technology, Cambridge, MA, 2012.
- [79] G. D'Antonio, J. S. Bedolla and P. Chiabert, "A novel methodology to integrate manufacturing execution systems with the lean manufacturing approach," in *The 27th International Conference on Flexible Automation and Intelligent Manufacturing*, 2017.
- [80] International Organization for Standardization (ISO), "ISO 50001: Energy management," ISO, Genève, 2011.
- [81] R. Maneschijn, "Developing a dynamic operational energy management strategy for energy intensive industries," PhD thesis, Faculty of Engineering, North-West University, Potchefstroom, 2017.

- [82] A. Moeuf, S. Tamayo, S. Lamouri, R. Pellerin and A. Lelievre, “Strengths and weaknesses of small and medium sized enterprises regarding the implementation of lean manufacturing,” in *IFAC-PapersOnLine*, vol. 49, no. 12, pp. 71–76, 2016.
- [83] W. A. Pelser, J. C. Vosloo and M. J. Mathews, “Results and prospects of applying an ISO 50001 based reporting system on a cement plant,” *Journal of Cleaner Production*, vol. 198, no. C, p. 642–653, 2018.
- [84] M. Schulze, H. Nehler, M. Ottosson and P. Thollander, “Energy management in industry: A systematic review of previous findings and an integrative conceptual framework,” *Journal of Cleaner Production*, vol. 112, p. 3692–3708, 2016.
- [85] TÜV UK Ltd, “ISO 50001 (EnMS) energy management systems,” TÜV NORD CERT GmbH, Croydon, 2014.
- [86] J. I. Bredenkamp, “An integrated energy management strategy for the deep-level gold mining industry,” PhD thesis, Faculty of Engineering, North-West University, Potchefstroom, 2016.
- [87] M. Van Heerden, “Improving DSM project implementations and sustainability through ISO standards,” MEng dissertation, Faculty of Engineering, North-West University, Potchefstroom, 2014.
- [88] P. Goosen, “Efficient monitoring of mine compressed air savings,” MEng dissertation, Faculty of Engineering, North-West University, Potchefstroom, 2013.
- [89] T. Fiedler and P. Mircea, “Energy management systems according to the ISO 50001 standard: Challenges and benefits,” in *The Applied and Theoretical Electricity International Conference (ICATE)*, Craiova, 2012.
- [90] E. W. Ottermann, “Energy management challenges and opportunities in the South African cement industry,” in *Proceedings of the 8th Conference on the Industrial and Commercial Use of Energy*, Cape Town, 2011.
- [91] W. A. Pelser, “A system for continuous energy management to improve cement plant profitability,” MEng dissertation, Faculty of Engineering, North-West University, Potchefstroom, 2016.

- [92] J. N. Du Plessis, "Development of a supervisory system for maintaining the performance of remote energy management systems," PhD thesis, Faculty of Engineering, North-West University, Potchefstroom, 2014.
- [93] J. H. Sono, "The effect of feedback on lower-level employees' empowerment, motivation and performance in a selected steel production company," MBA mini-dissertation, School of Business & Governance, North-West University, Potchefstroom, 2014.
- [94] W. Booysen, "Measurement and verification of industrial DSM projects," PhD thesis, Faculty of Engineering, North-West University, Potchefstroom, 2014.
- [95] 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, p. 108–119, 2014.
- [96] N. Salahi and M. A. Jafari, "Energy-performance as a driver for optimal production planning," *Applied Energy*, vol. 174, p. 88–100, 2016.
- [97] E. Worrel, L. Price, N. Martin, J. Farla and R. Schaeffer, "Energy intensity in the iron and steel industry: A comparison of physical and economic indicators," *Energy Policy*, vol. 25, p. 737–744, 1997.
- [98] Efficiency Valuation Organization, "International performance measurement and verification protocol: Concepts and options for determining energy and water savings," Efficiency Valuation Organization, Toronto, 2012.
- [99] Nexant Inc., "M&V guidelines: Measurement and verification for federal energy projects," US Department of Energy Federal Energy Management Program, Washington, DC, 2008.
- [100] J. Bažan and J. Kret, "Iron and steelmaking," VSB – Technical University of Ostrava, Ostrava, 2015.
- [101] M. Mäkela, "Assessing potential forest and steel inter-industry residue utilisation by sequential chemical extraction," PhD dissertation, School of Chemical Technology, Aalto University, Espoo, 2012.
- [102] L. E. Zeelie, "Compressed air energy savings on an iron production plant," MEng dissertation, Faculty of Engineering, North-West University, Potchefstroom, 2016.

- [103] M. Yi and J. Mao-fa, "Exergy analysis and optimisation of ladle furnace refining process," *Journal of Iron and Steel Research, International*, vol. 17, no. 11, p. 24–28, 2010.
- [104] M. Shamanian and A. Najafizadeh, "Hot charge of continuously cast slabs in reheating furnaces," *International Journal of ISSI*, vol. 1, pp. 35-37, 2004.
- [105] E. Pretorius and H. Oltmann, "EAF fundamentals," Process Technology Group – LWB Refractories.

Appendices

The appendices contain additional information for the study, which were referred to throughout the thesis. This information contributes to the knowledge and background of the reader, but does not necessarily contribute to the flow of the document.

APPENDIX A: STEELMAKING METHODS

A.1 OVERVIEW OF STEEL PRODUCTION

Overview

There are different process that can be used to manufacture steel. The main methods are referred to as the blast furnace – basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF) [14, 15]. About 25% of steel is produced using the EAF method, while the other 75% is produced using the BF-BOF approach [15]. Another steelmaking technology, referred to as the open hearth furnace method, accounts for about 0.5% of global steel production [14]. This process is not widely used due to its high energy intensity and the economic and environmental disadvantages it entails [14]. A basic overview of the different steel production methods are provided in Figure 55 [15], followed by a detailed discussion.

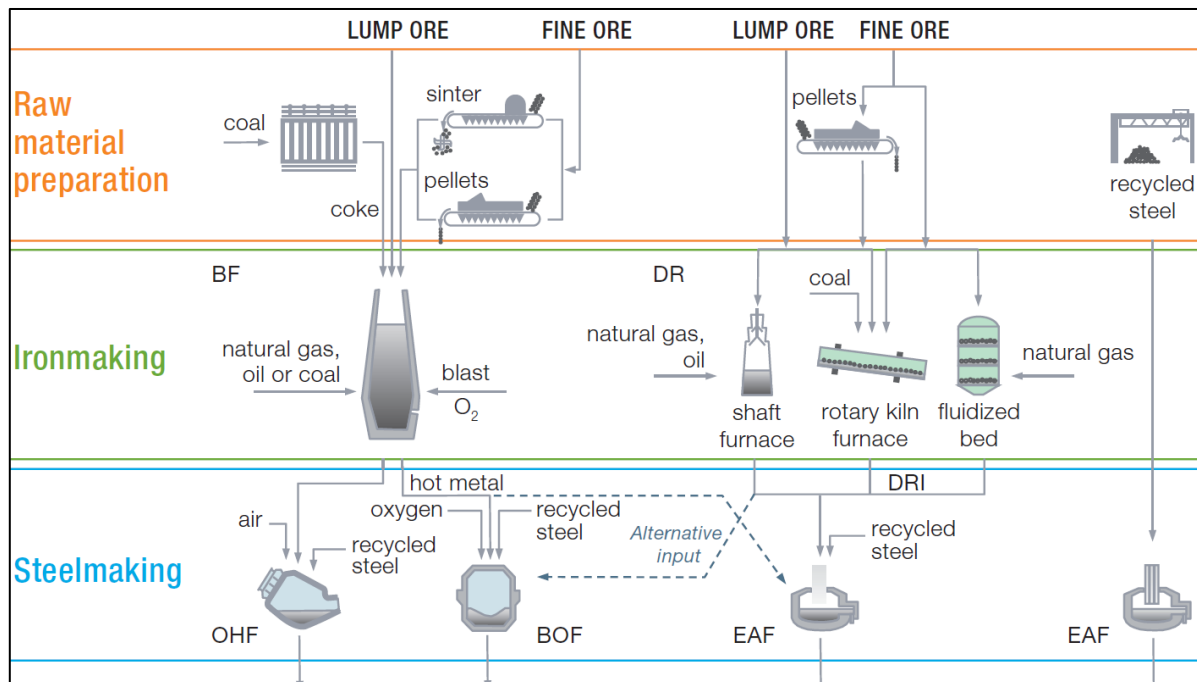


Figure 55: Different methods for steel production [15] (first presented in Figure 3)

BF-BOF production method

The first step in the BF-BOF production method is producing liquid iron in the blast furnace. This step depends on several preparatory operations to provide the blast furnace with the necessary raw materials. This step includes operations such as a coke plant, sinter plant and hot blast stove. The use of a blast furnace includes charging it with ore, fluxes and fuel to produce iron in liquid form. This process of producing iron is continuous, and cannot be stopped and restarted as needed [100, 101, 102].

The liquid iron is then refined to steel in the BOF by using an oxygen blow, resultantly removing material impurities and adjusting the level of carbon [101]. The next step is finalising the quality of liquid steel as part of the secondary metallurgy (SecMet) section before it is sent to the continuous caster (concast) [101]. One of the components in SecMet is a ladle furnace, which is a high electrical energy consumer that uses a three-electrode electric system.¹² The main purpose of the ladle furnace is refining the liquid steel according to its quality requirements, and ensuring that the temperatures are at the desired levels for the concast [47, 103].

At the concast, molten steel flows slowly from a tundish and continuously solidifies into slabs at the bottom of the caster. Consecutive casts of the same steel quality is referred to as a sequence, which may not be interrupted due to cost and production delay complications [47]. This complicates production scheduling on a steelmaking facility. Production planners have to consider the following factors when compiling the casting schedule: the limitations of the casters, product delivery dates and requirements of the rolling mills [47]. The rest of the steel plant has to adapt to the schedule compiled for the concast.

From the concast, steel slabs can follow different production routes, such as being sent to a stockpile or being processed by the hot rolling mill [104]. A hot rolling mill consists of a reheating furnace, where steel is typically heated to about 1 200°C whereafter it is formed by several sets of cylinders or rolls.¹² In terms of energy cost reduction, the most economic route is for casted slabs to be charged directly into the reheating furnace. This ensures that a minimum amount of extra heat is required before rolling the steel into the desired profiles [104]. This is referred to as direct loading (if steel is loaded into the furnace directly after casting) or hot charging (if it takes place within 12 hours after casting) [37]. Coordinating hot charging to reduce reheating furnace energy consumption is another challenge in production planning.

EAF method

The EAF method mainly uses recycled steel (scrap) as an input for the production process. It is also possible to add direct reduced iron (DRI) for chemical balance, as seen in Figure 55. The temperature of the content is increased to about 1 600°C in the EAF by using electrodes to conduct electrical energy, and thereby melting the content into high-quality steel. Impurities are then removed from the steel by adding fluxes and removing the slag through the taphole [15, 105]. An example of an EAF is presented in Figure 56.

¹² Ingeteam, "Secondary metallurgy: Ladle furnaces," Ingeteam, n.d. [Online]. Available: https://www.ingeteam.com/au/en-au/sectors/steel-metals/p15_29_528_525/secondary-metallurgy-ladle-furnaces.aspx. [Accessed 19 February 2018].

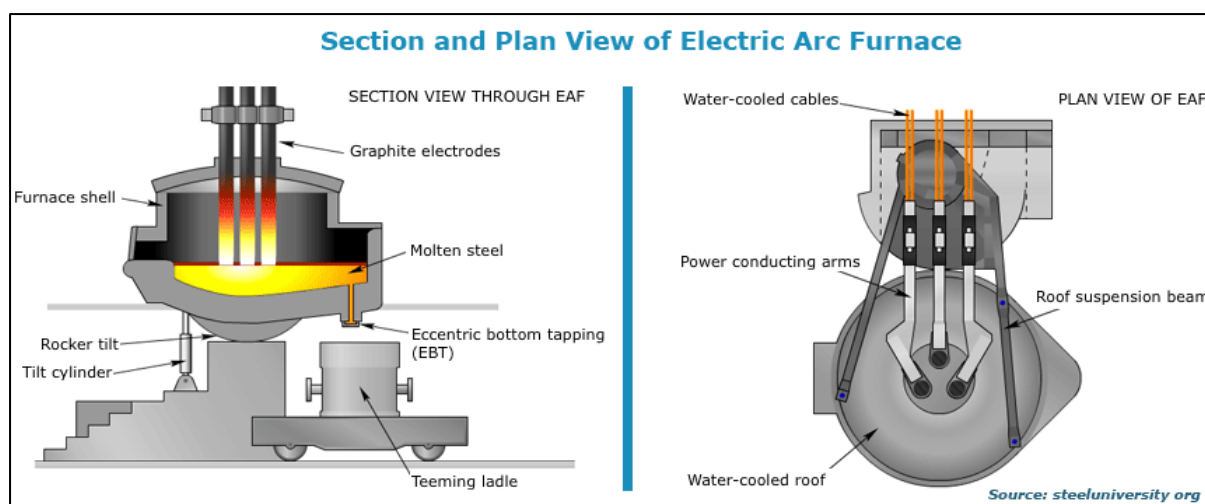


Figure 56: Illustrative layout of an EAF¹³

An EAF is able to produce a batch of steel (also referred to as a *heating cycle*) in less than an hour. Current technology for EAFs injects gases (oxygen and natural gas) into the furnace, which improved the process from its original operation. The electrical energy consumption of a heating cycle is reported to be between 380 kWh/t and 400 kWh/t. Electricity is generated from various energy sources, including coal. It is estimated that about 150 kg of coal is required to generate the electrical energy required to produce 1 tonne of steel in an EAF.¹⁴ The liquid steel produced by the EAF then follows the same route to the ladle furnace, concast and rolling mills. The planning of this process is more manageable than the BF-BOF method due to the batch production of the EAF.

A.2 ENERGY CONSUMPTION IN STEEL PRODUCTION

The EAF method is reported to be much less energy intensive than the BF-BOF method [14]. The energy intensities per tonne steel for the major energy consuming components are provided in Figure 57 [14]. These components are used in the different methods presented in Figure 55. This representation shows that the blast furnace is the most energy intensive component in a steelmaking facility. Several factors will, however, have an effect on the energy consumption of a plant, such as the components used to produce steel; the size of the plant; the quality of the iron ore; quality control; and the efficiency of waste energy recovery [14].

¹³ Institute for Industrial Productivity, "Industrial efficiency technology database: Electric arc furnace," Institute for Industrial Productivity, n.d. [Online]. Available: <http://ietd.iipnetwork.org/content/electric-arc-furnace>. [Accessed 22 February 2018].

¹⁴ World Coal Association, "How is steel produced?," World Coal Association, 2018. [Online]. Available: <https://www.worldcoal.org/coal/uses-coal/how-steel-produced>. [Accessed 24 February 2018].

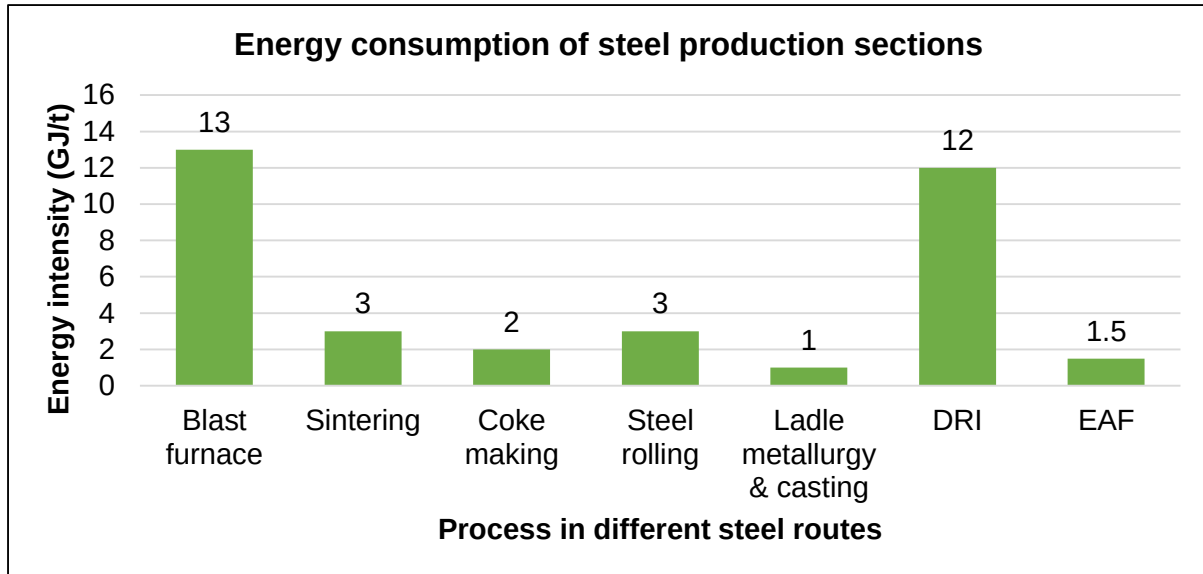


Figure 57: Energy consumption of major energy consuming components [14]

There are significant differences between the energy efficiency of iron and steel production plants, with an estimated gap of 50% efficiency between the best and worst BF-BOF plants [14]. Energy efficiency improvement opportunities in the steelmaking industry have been quantified to be 20% worldwide [14]. This serves as an indication that ample opportunities exist to reduce costs in steel production by focusing on energy management.

APPENDIX B: THEORETICAL EVALUATION OF PERFORMANCE FROM HISTORICAL DATA

B.1 PREAMBLE

This appendix provides a detailed discussion of the performance of the identified initiatives from historical data, as referred to in Step E.3 of Section 4.3.3. A summary of the findings in this appendix is provided in Table 18 (Section 4.3.3). The purpose of this discussion is to evaluate whether sufficient variation exists between different scenarios for initiatives. This will serve as an indication of whether potential benefits exist to motivate the implementation of an initiative, and can be used as part of the dynamic prioritisation of initiatives during its integration. Each initiative is discussed individually below.

B.2 HOT CHARGING OF THE PRIMARY ROLLING MILL FURNACE

It was noted in Step E.1 (Section 4.3.3) that hot charging of the primary rolling mill furnace does take place, but that it is not considered as being effective. The hot charging performance for 2016 was analysed, and it was found that a hot charging rate of 27% was achieved during this period. This is lower than the targeted hot charging rate of 40%, as determined by plant management. The total tonnes produced and tonnes hot charged for each month of 2016 are provided in Table 30. This table shows that the hot charging target of 40% was achieved during June 2016, and that it is a realistic target.

Table 30: Primary rolling mill furnace production and hot charging

Month	Production (t)	Hot charging (t)	Hot charging (%)
Jan 2016	98 270	28 376	29%
Feb 2016	99 907	37 249	37%
Mar 2016	97 510	21 485	22%
Apr 2016	113 504	37 695	33%
May 2016	106 430	25 172	24%
Jun 2016	99 928	39 511	40%
Jul 2016	107 268	16 382	15%
Aug 2016	90 187	26 042	29%
Sep 2016	110 033	33 102	30%
Oct 2016	96 752	19 873	21%
Nov 2016	90 240	20 635	23%
May 2016	83 081	16 949	20%
Total	1 193 110	322 471	27%

To evaluate the effect that hot charging has on the energy consumption of the furnace, gas consumption data was collected and compared with production on a daily basis. The historical data was isolated according to the daily hot charging percentage achieved. Percentage ranges of 20% ($10\% \pm 10\%$, $30\% \pm 10\%$, etc.) were used to isolate days according to their hot charging performance. Data sets were compiled for each range. Regressions models of furnace production versus furnace gas consumption were generated for each range. Figure 58 provides the regression lines for days with 0% to 20% hot charging ($10\% \pm 10\%$).

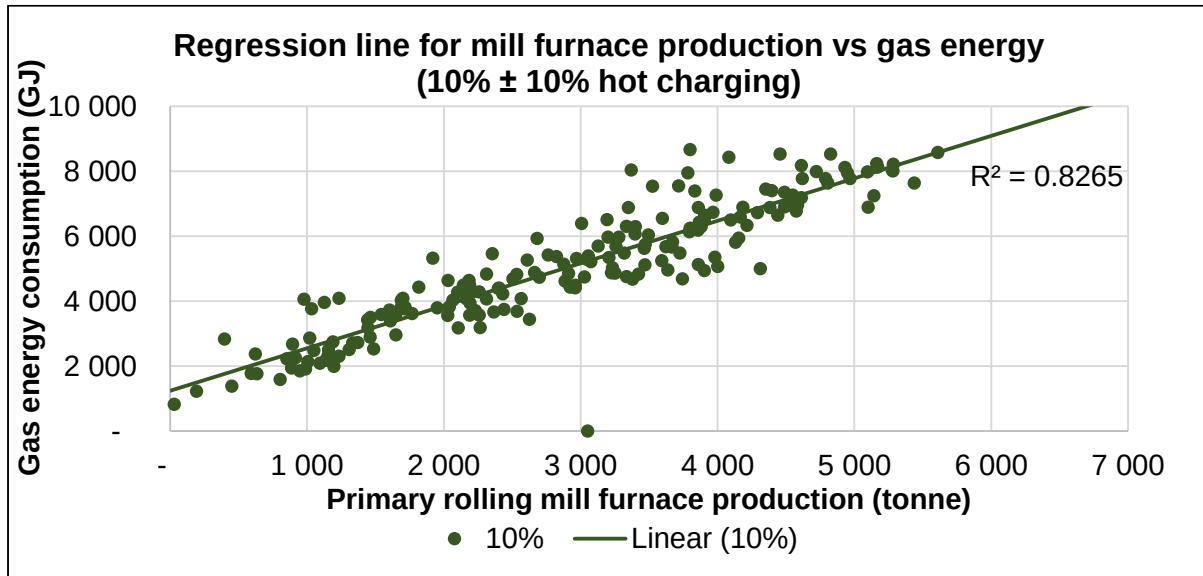


Figure 58: Regression line for $10\% \pm 10\%$ hot charging range

Figure 59 provides the regression lines for days with 20% to 40% hot charging ($30\% \pm 10\%$).

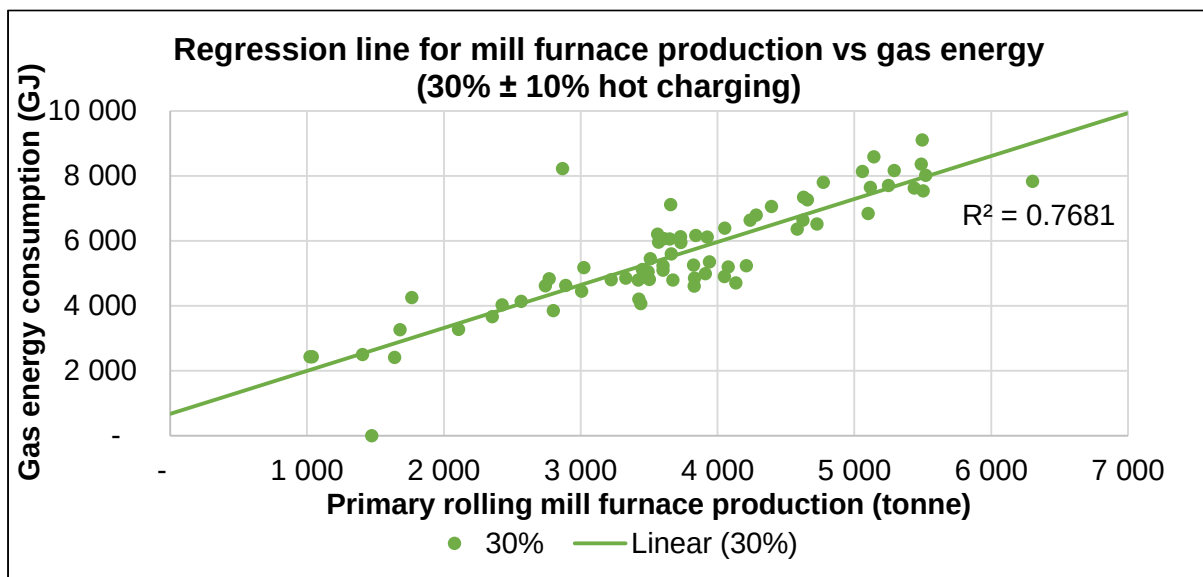


Figure 59: Regression line for $30\% \pm 10\%$ hot charging range

Figure 60 provides the regression lines for days with 40% to 60% hot charging ($50\% \pm 10\%$).

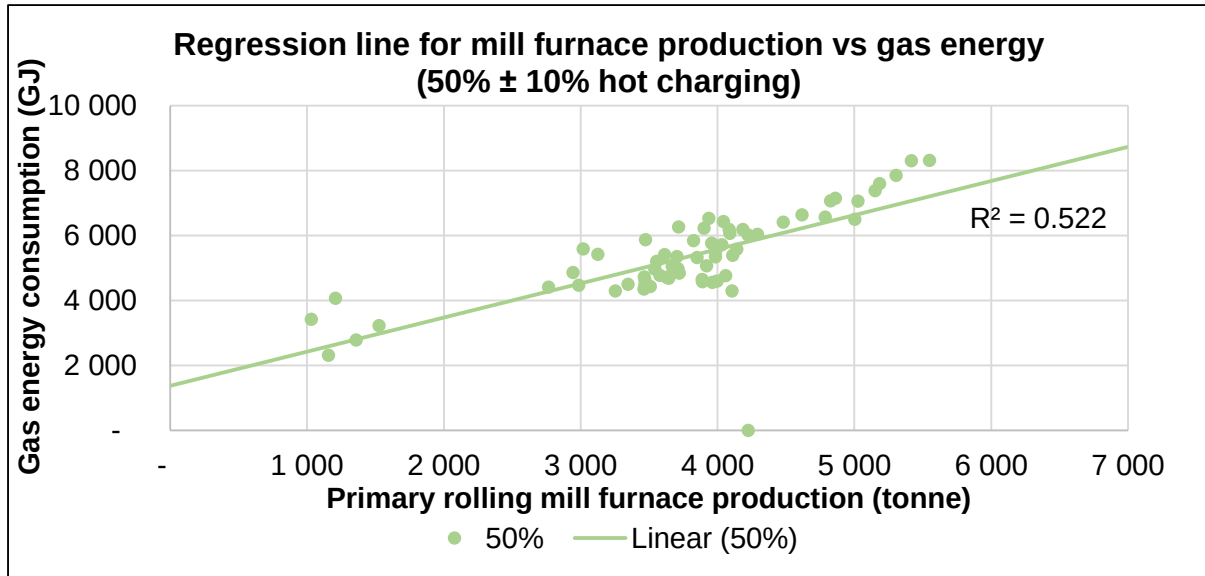


Figure 60: Regression line for 50% ± 10% hot charging range

Figure 61 provides the regression lines for days with 60% to 80% hot charging (70% ± 10%).

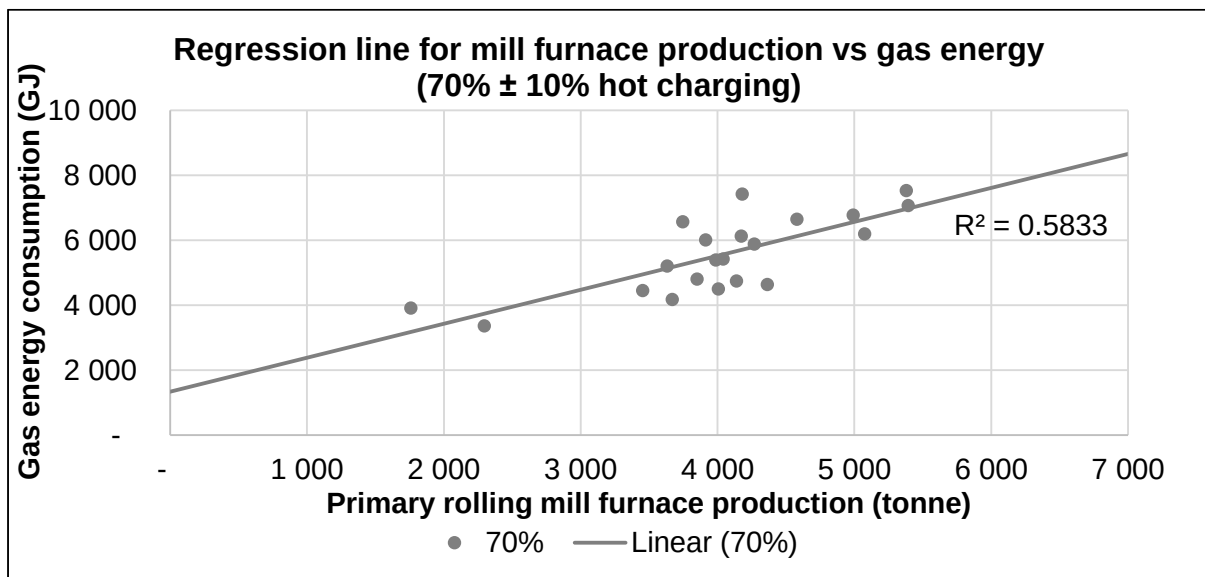


Figure 61: Regression line for 70% ± 10% hot charging range

Figure 62 provides the regression lines for days with 80% to 100% hot charging ($90\% \pm 10\%$).

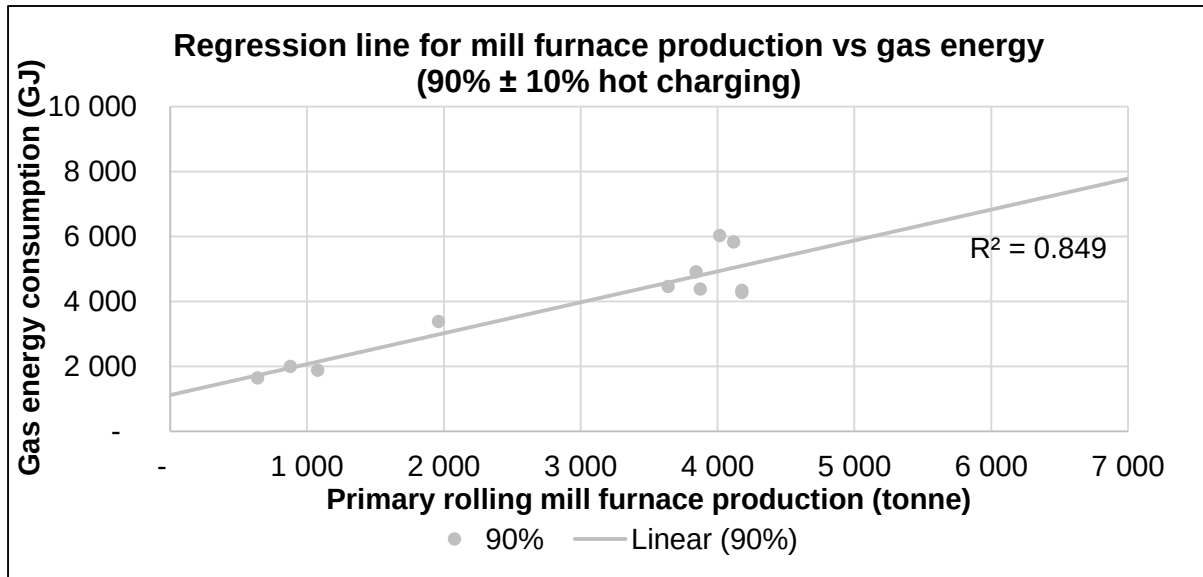


Figure 62: Regression line for $90\% \pm 10\%$ hot charging range

A summary of the resulting regression lines is provided in Figure 63.

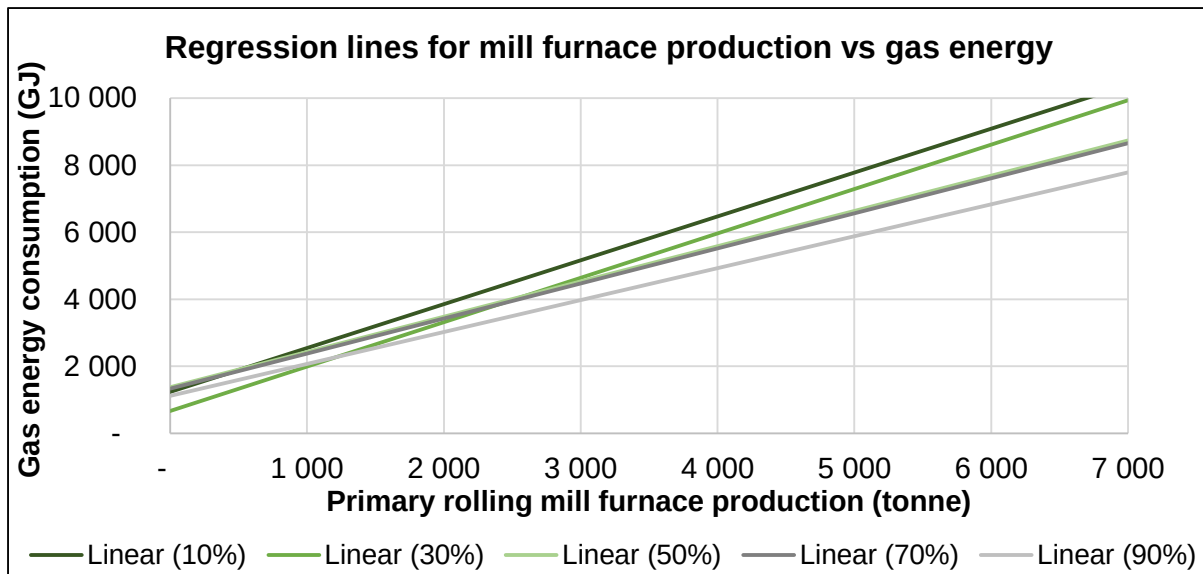


Figure 63: Regression lines for hot charging ranges

Figure 63 shows that there is variation in the energy consumption due to the percentage hot charging. Figure 63 indicates that a higher percentage hot charging results in lower energy consumption, which motivates the use of hot charging to improve the cost efficiency of the primary rolling mill furnace. The regression lines could all be represented by a straight line, with the independent variable (x) being production, and the dependent variable (y) being gas energy consumption. Equation 9 gives the straight line formula (first presented in Equation 4).

Equation 9: Straight line formula (first presented in Equation 4)

$$y = mx + c$$

The straight line formula for each regression model was used to estimate the gas consumption for the year, based on the daily production tonnages (input each day in x and calculate y). This made it possible to calculate the gas consumption for each day if a different hot charging percentage was achieved. This was subtracted from the actual gas consumption, resulting in the estimated gas consumption reduction. The average daily gas consumption reduction for 2016 was used to estimate the gas consumption reduction per day (GJ/day) for each range evaluated in Figure 63. By using the average gas cost of R62/GJ for 2016, the theoretical cost benefit could be calculated for each range. These results are presented in Table 31.

Table 31: Estimated gas reduction for hot charging percentage ranges

Range ($\pm 10\%$)	m	c	Estimated gas reduction (GJ/day)	Estimated gas reduction (R/day)
10%	1.309	1 245	-346	-R21 439
30%	1.324	674	174	R10 810
50%	1.051	1 377	360	R22 344
70%	1.046	1 337	420	R26 020
90%	0.951	1 122	942	R58 422

Table 31 shows that the estimated gas reduction for $10\% \pm 10\%$ is negative. This is due to the actual hot charging percentage of 27% for 2016 being higher than this range. To calculate the theoretical cost benefit of hot charging, this value had to be added to the estimated gas reduction for each day, as per Table 32. These values can be used as the estimated variation between hot charging percentage scenarios for further calculations.

Table 32: Theoretical cost benefit of hot charging percentage ranges

Range ($\pm 10\%$)	Theoretical cost benefit (R/day)
10%	R0
30%	R32 249
50%	R43 782
70%	R47 458
90%	R79 861

As a further method of indicating the effect that increased hot charging has on energy consumption and production of the primary rolling mill furnace, the percentage hot charging and energy intensity were plotted on the same graph for a selected month. December 2016 was chosen as an example, and the effect is presented in Figure 64. The energy intensity (GJ/t: primary y-axis) is representative of the energy consumption and production. This representation shows that the hot charging percentage reduced from the middle of the month, causing an increase in energy intensity. This graph can prove to be valuable when discussing the benefits of hot charging with plant personnel.

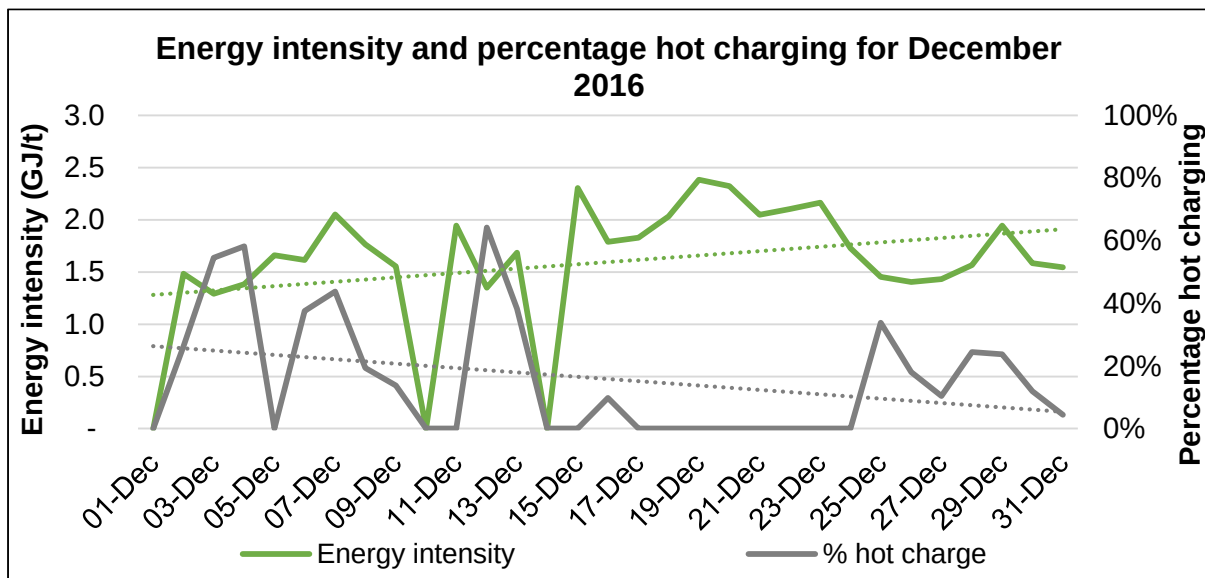


Figure 64: Effect of hot charging on energy intensity (example for December 2016)

The effect that hot charging has on production and energy consumption was evaluated by isolating days where the target of 40% was reached from those days where it was not. The average production and gas consumption were calculated for the isolated scenarios, as indicated in Figure 65. Figure 65a shows that reaching the targeted 40% resulted in estimated production increases of 525 t/day (16%). Figure 65b indicates that reaching the target resulted in estimated gas consumption reductions of 70 GJ/day (1%).

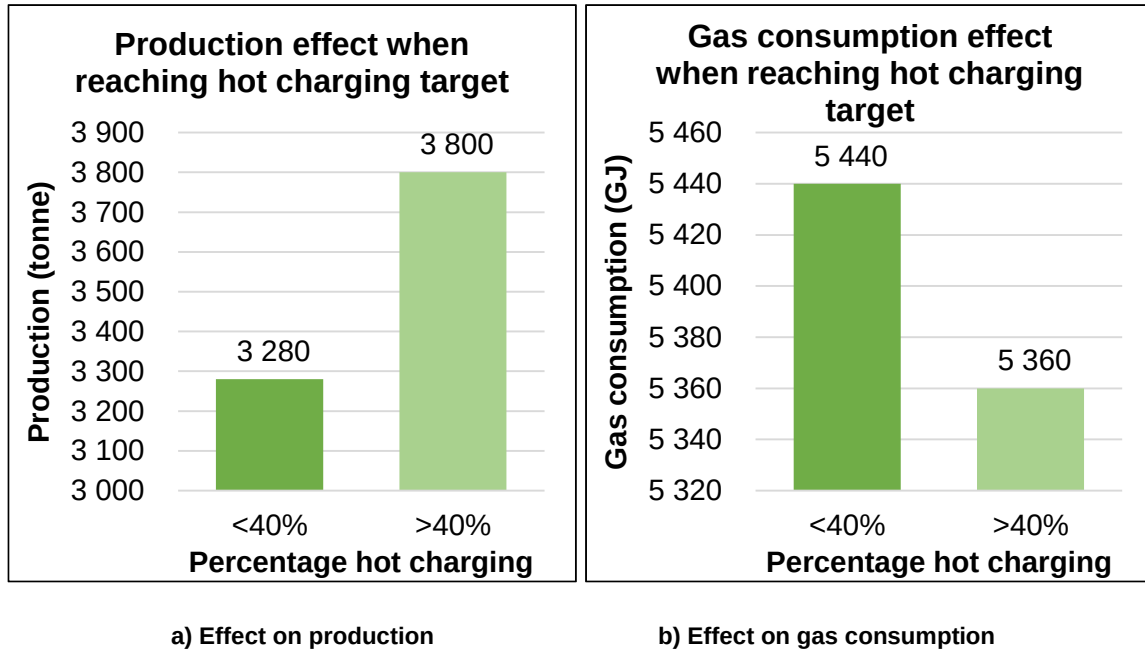


Figure 65: Hot charging effect on production and gas consumption

A similar calculation was used to determine the effect on the energy intensity when reaching the hot charging target, as indicated in Figure 66. The energy intensity reduction of 0.3 GJ/t (15%) observed in Figure 66 is representative of the combined effect that increased hot charging has on the primary rolling mill furnace's production and energy consumption.

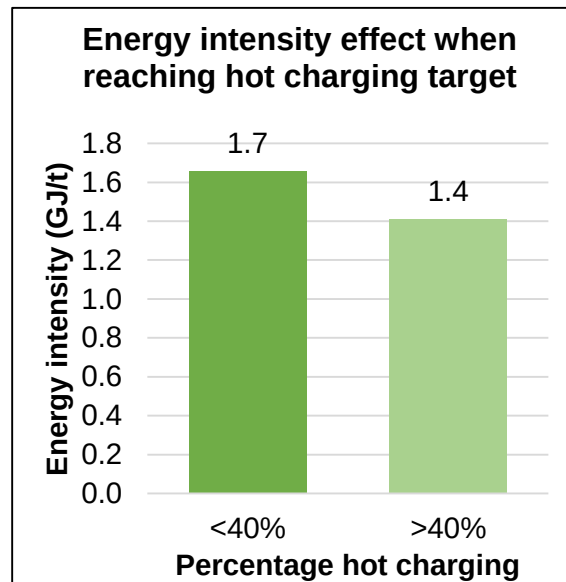


Figure 66: Hot charging effect on energy intensity

Based on the analysis of historical performance, it can be concluded that sufficient variation exists between scenarios to achieve a cost benefit from increased hot charging on Plant X.

B.3 LADLE FURNACE LOAD SHIFTING

The next initiative that was identified from literature is load shifting of the ladle furnaces' electrical energy consumption. Due to the continuous production nature of the BF-BOF process, it is not possible to stop and start production as needed, which resultantly induce delays. It was decided to evaluate the variance in energy intensity of different steel qualities. The steel qualities produced by the facility are described in Appendix C. Data for the energy consumption per heating cycle was obtained for 2016, along with the steel quality produced. The average energy consumption per heating cycle of each steel quality was determined from this data.

The average energy consumption for each steel quality is provided in Appendix D. The steel qualities were split between Production Route 2 and Production Route 3 steel qualities, as steel qualities produced using Production Route 3 typically have more additives, which resultantly require more energy at the ladle furnaces to reach the required temperatures for casting. As an example, the frequency plots of two steel qualities (Steel Quality 20 and Steel Quality 26) are presented in Figure 67 on the same axis. These plots show that there is a variation of 1.3 MWh/heat between these steel qualities.

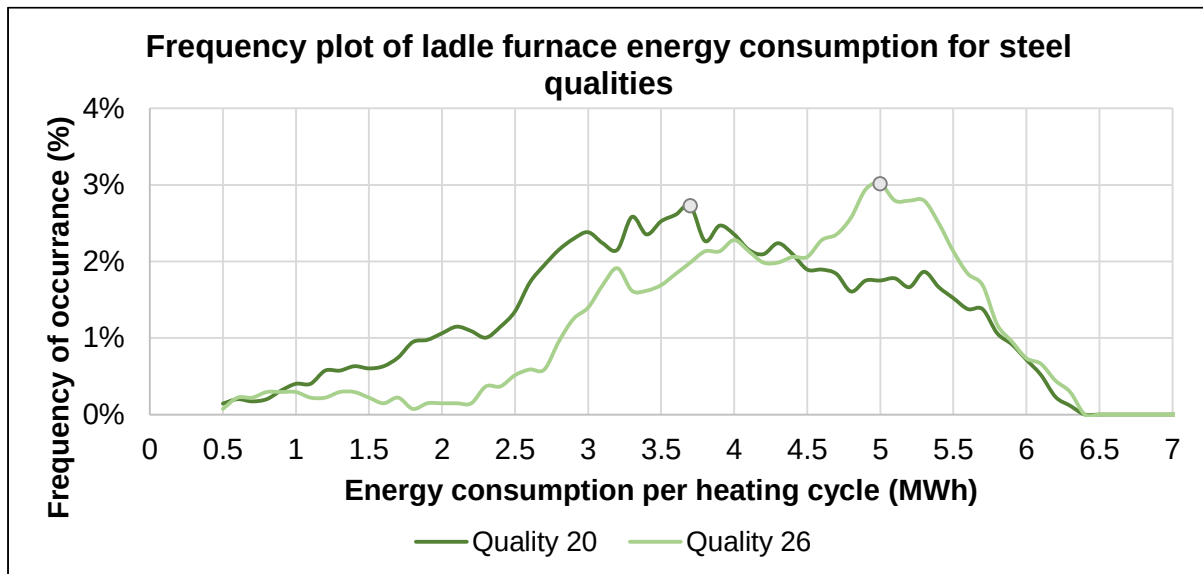


Figure 67: Frequency plot of ladle furnace energy consumption of two steel qualities

The variation between the energy consumption of the different ladle furnaces was also evaluated, and is presented in the form of a frequency plot in Figure 68. This graph shows that there is a variation of 1.2 MWh/heat between the ladle furnaces.

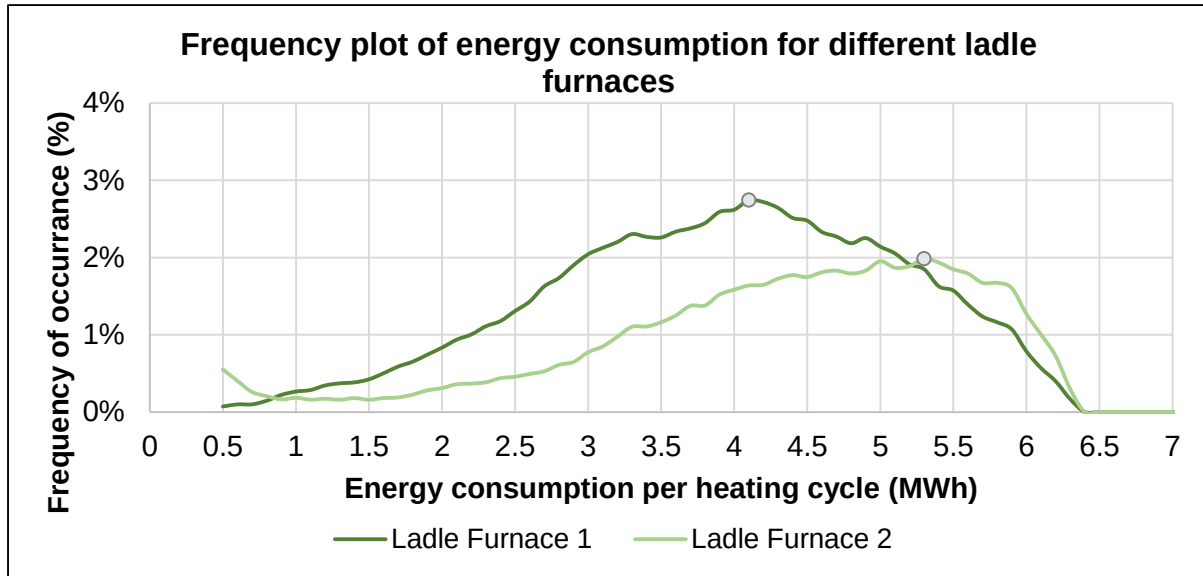


Figure 68: Frequency plot of energy consumption of different ladle furnaces

In order to account for all of the steel qualities and production routes, the minimum, maximum and average ladle furnace energy consumption per heating cycle were evaluated, as per Figure 69. This representation shows that there is a large variance in the highest and lowest energy consuming steel qualities. The variation for the Production Route 2 steel qualities is less than that of Production Route 3 steel qualities, as expected. The maximum variation (and resultantly maximum theoretical benefit) for the respective production routes were calculated as 1.9 MWh/heat for Production Route 2 and 5.7 MWh/heat for Production Route 3.

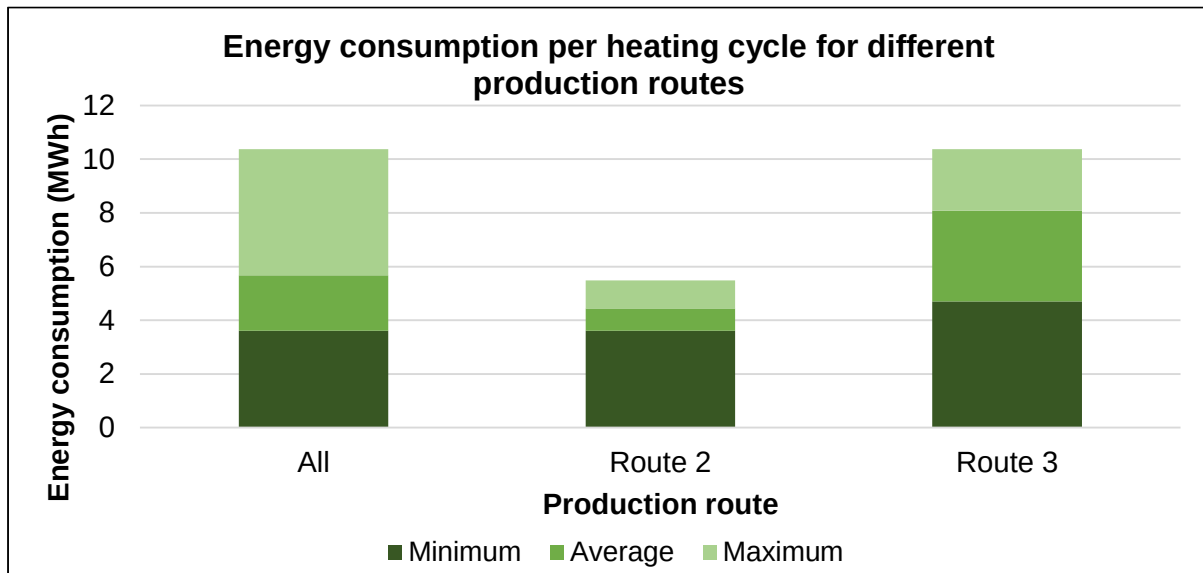


Figure 69: Energy consumption variation per heating cycle for different production routes

To quantify the maximum theoretical cost benefit, two scenarios were compared for each production route using the relevant TOU electricity tariffs for Plant X for the high demand season (winter). The worst-case scenario is if the highest energy consuming steel quality is produced in peak time, and the lowest energy consuming steel quality is produced in off-peak time. The best-case scenario is if the lowest energy consuming steel quality is produced in peak time, and the highest energy consuming steel quality is produced in off-peak time. Both scenarios are presented for the different production routes in Figure 70. The difference between the scenarios provides the maximum theoretical cost benefit per heating cycle, and was calculated as R4 500 for Production Route 2 and R13 200 for Production Route 3 steel qualities.

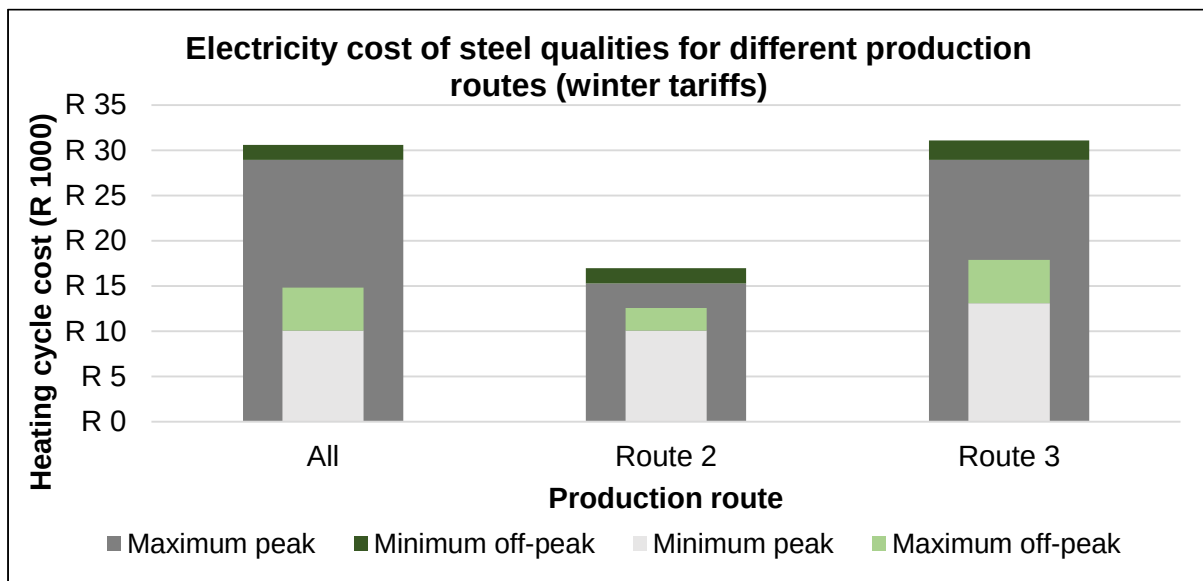


Figure 70: Best- and worst-case scenario energy costs for different production routes

As there are five peak hours in a weekday, and assuming that a heating cycle takes one hour, the maximum daily benefit could be calculated by multiplying the maximum theoretical benefit per heating cycle by 5. The maximum potential cost benefits per day in the winter are calculated as R22 500 for Production Route 2 and R66 000 for Production Route 3 steel qualities. Based on this analysis of historical data, it can be concluded that sufficient variation exists between scenarios to achieve a cost benefit from ladle furnace load shifting at Plant X.

B.4 LADLE AND CRANE TIME LOSS REDUCTION

As discussed in Step E.2 (Section 4.3.3), only selective data is available for the ladle and crane time loss reduction initiative that was identified from literature. The start and end times of each step in the production process of the steelmaking facility was the only viable data that was available historically. This data was used to determine the time of movement between the different steps. Additionally, the ladle furnace used was also available. The transfer times

between the BOFs and the different ladle furnaces were calculated, which are presented in the frequency plot of Figure 71. This plot shows that the transfer time from the BOF to Ladle Furnace 2 is two minutes less than the transfer time from the BOF to Ladle Furnace 1.

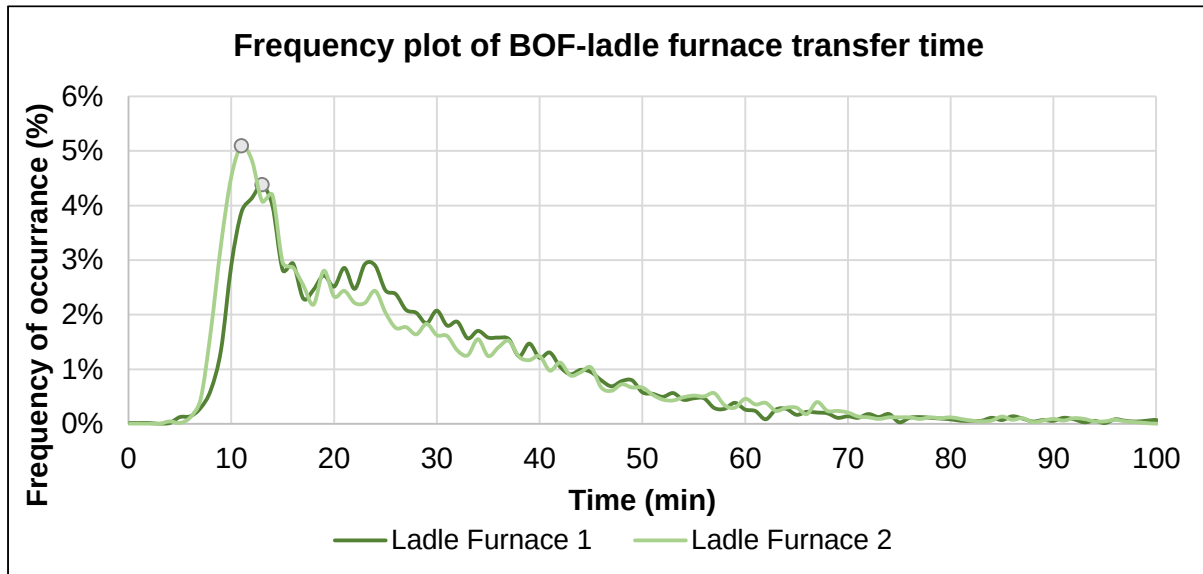


Figure 71: Frequency plot of BOFs to ladle furnace transfer times

A similar calculation was done to determine the transfer time between the different ladle furnaces and the concast, as per the frequency plot in Figure 72. This representation shows that the transfer time from Ladle Furnace 2 to the concast is approximately 1 minute less than the transfer time from Ladle Furnace 1 to the concast. Accumulatively, it is estimated that the use of Ladle Furnace 2 would reduce the transfer time (crane usage) by 3 minutes.

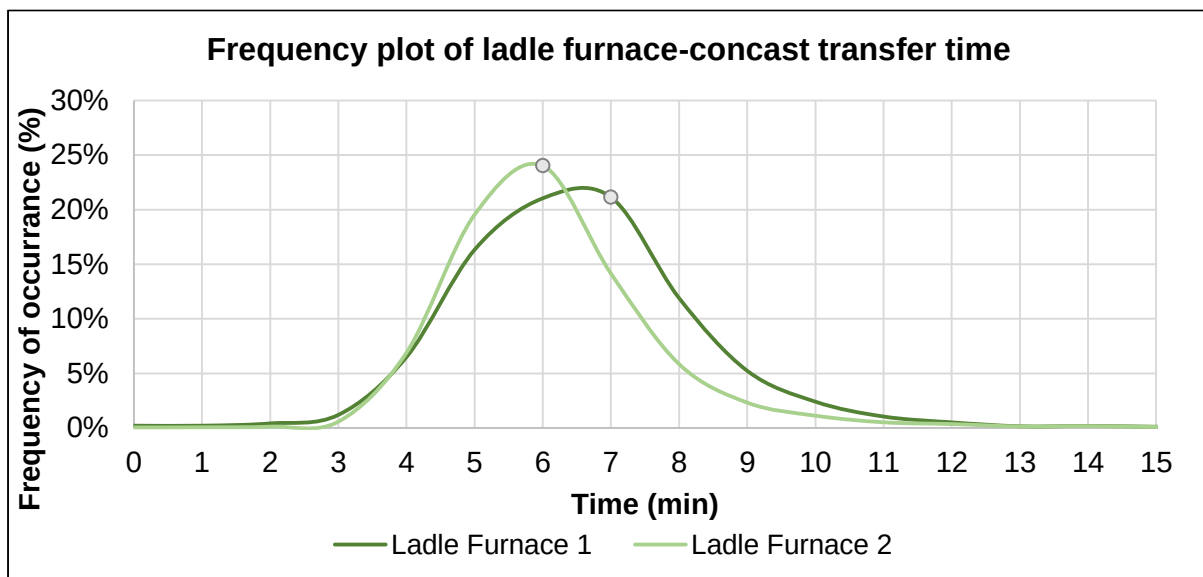


Figure 72: Frequency plot of ladle furnace to concast transfer times

In order to determine the effect of a reduction in transfer time it was attempted to quantify the loss in steel temperature and increased energy consumption at the ladle furnaces due to time losses. Regression models of the ladle furnace-concast transfer time versus temperature reduction (Figure 79), BOF-ladle furnace transfer time versus temperature reduction (Figure 80), and BOF-ladle furnace transfer time versus ladle furnace energy consumption (Figure 81) are presented in Appendix E. These regression models show that the increased transfer times do not have a clear effect on the temperature or energy consumption.

A further quantification of a reduction in transfer time was investigated by evaluating the average casting duration of a ladle at the concast, as per the frequency plot in Figure 73. This plot shows that the average time for a ladle to be casted is 50 minutes. The effect of a three-minute reduction in transfer time is about 6% of the casting time, which translates to a 6% increase in production. At an average steel content of 150 t/ladle, which is calculated as a production increase of about 9.6 tonnes per cast.

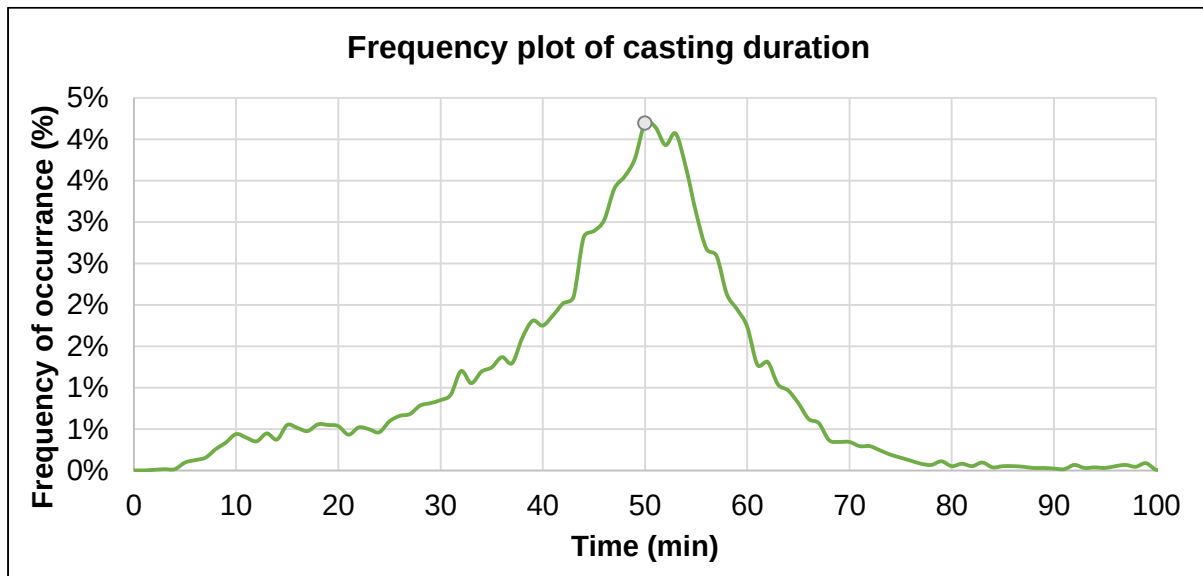


Figure 73: Frequency plot of casting duration

In order to determine whether there was any lost opportunity in 2016, the use of Ladle Furnace 1 while Ladle Furnace 2 was available was evaluated. Apart from maintenance time, it was found that Ladle Furnace 1 was used 16% of the time while Ladle Furnace 2 was available. This serves as an indication that there is some opportunity for reduced transfer times. In order to quantify the increased production as a cost benefit, however, it is required for the plant to operate at maximum production capacity. A time reduction will not be beneficial to a plant that is not able to utilise the time saving to increase production outputs.

The analysis of historical data indicates that Plant X never operated at maximum capacity during 2016, and that the additional time saving would not have been utilised as an increase

in production. It is thus concluded that there is limited variation between scenarios for this initiative. Even though some variation does exist, it is not possible to utilise it as a cost benefit for Plant X.

B.5 PRIMARY ROLLING MILL APPORTIONMENT MODEL

Step E.2 (Section 4.3.3) showed that some of the data for the analysis of the apportionment model has limited availability. The temperatures inside the furnace are not logged properly, and could only be obtained for a period of one month. The analysis of the apportionment model was conducted based on data from March 2017. During the identification of the initiative from literature it was discussed that the size and quality of steel blooms into the furnace could have an effect on the heating quality inside the furnace (and possibly also the energy consumption). At Plant X, however, all the blooms loaded into the furnace are of the same size, and the only variation is in the quality of the steel (as per Appendix C).

The gas consumption and temperatures inside the furnace for different steel qualities processed during this time were analysed. The expected effect is that some steel qualities will require more gas to maintain the specified temperatures inside the furnace due to the different thermal performance. The gas flow (m^3/h) required to maintain the required average temperature ($^{\circ}\text{C}$) inside the furnace was evaluated as an intensity of flow per temperature ($\text{m}^3/\text{h}/^{\circ}\text{C}$) for the different steel qualities, and is presented in Figure 74. A summary of the gas consumption, average furnace temperatures and intensities for the different steel qualities is presented in Table 36 in Appendix F.

Figure 74 (and Appendix F) shows that there is variation between the intensities of different steel qualities. The purpose of the apportionment model is, however, to group steel qualities with similar specifications together in the furnace to improve the heating quality and stability of the furnace. A scenario where steel qualities with different specifications were grouped in the furnace was compared with a scenario where the same steel quality was produced consecutively, and the results were compared.

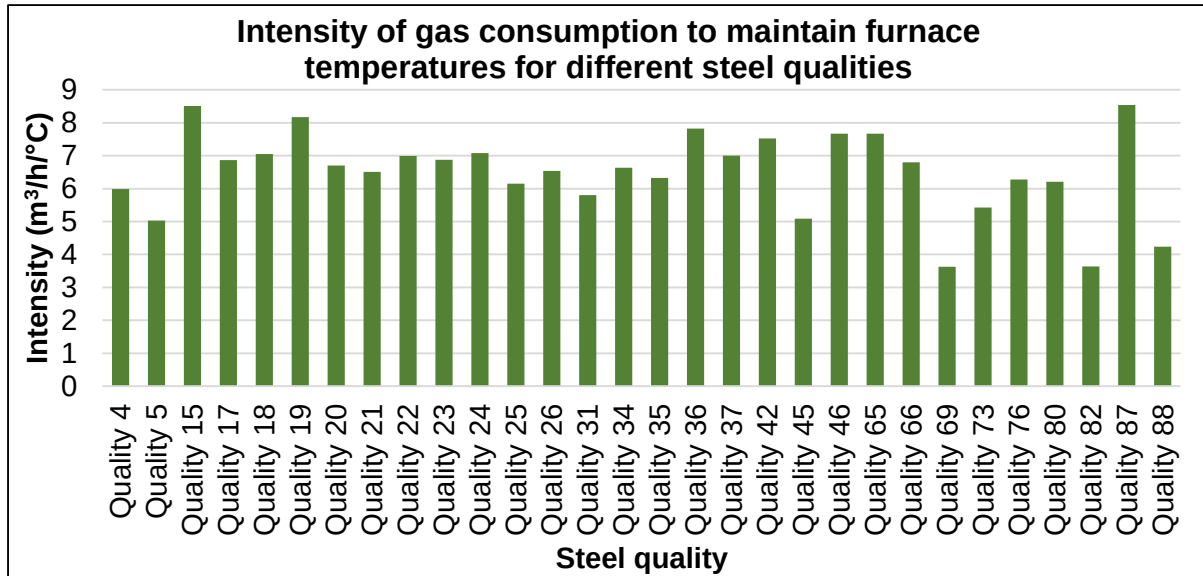


Figure 74: Intensity of gas flow to maintain furnace temperature for steel qualities

The example in Figure 75 provides an example where several different steel qualities are produced consecutively in the furnace. The expected effect of average furnace temperature variation is observed in this example as the furnace temperature is unstable when steel qualities are varied.

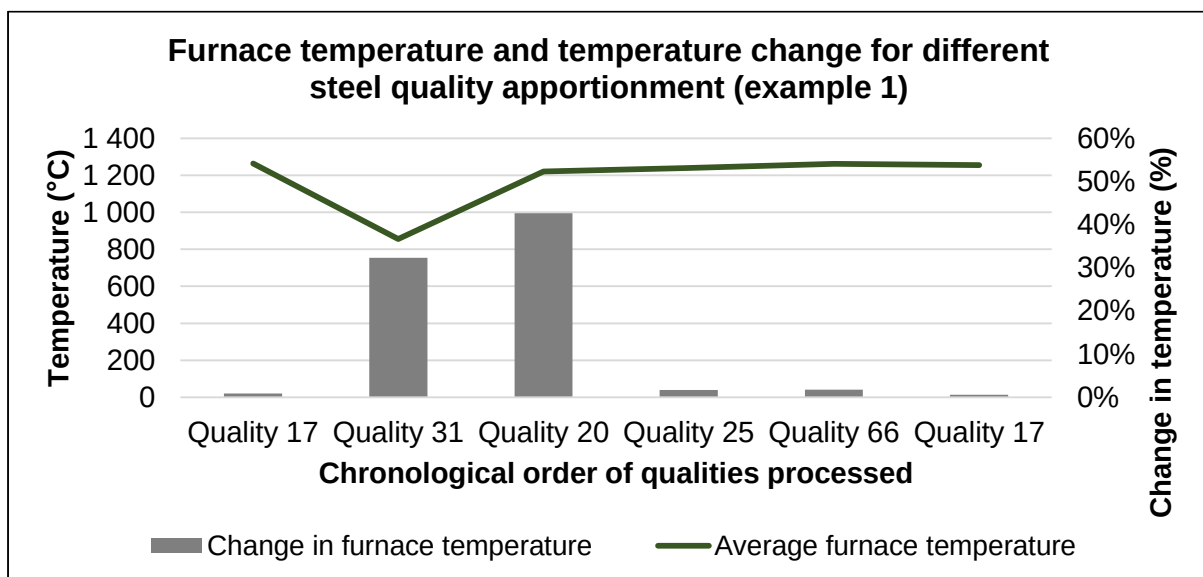


Figure 75: Example of the effect of steel qualities on average furnace temperature

On the other hand, Figure 76 provides an example where the same steel quality is processed consecutively in the furnace. Contrary to what is expected, it is observed that the average furnace temperature is also unstable for this scenario.

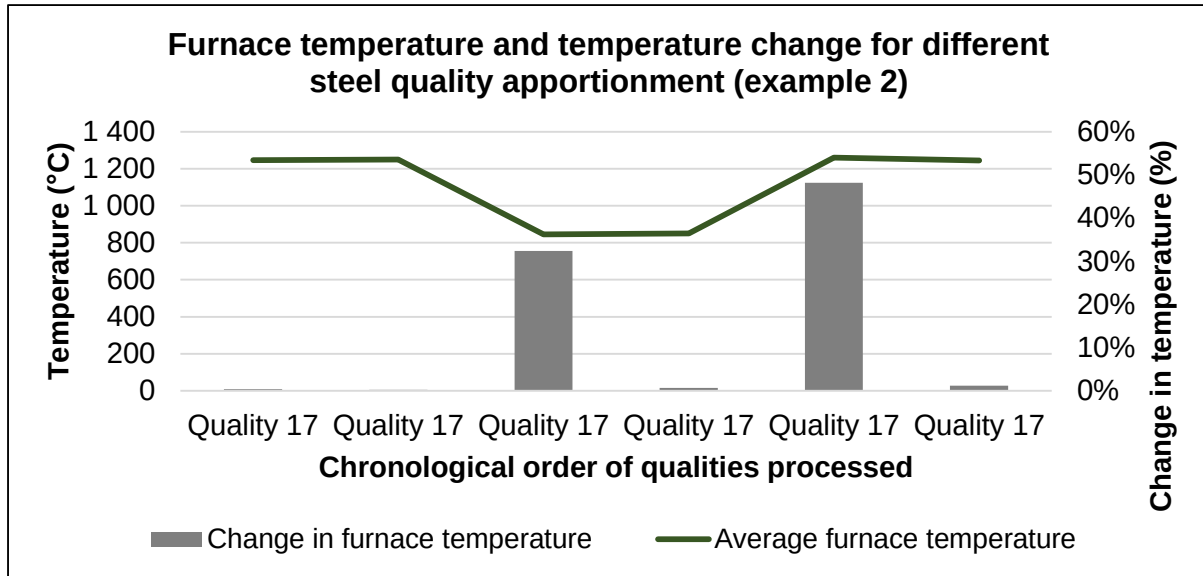


Figure 76: Example of the effect of one steel qualities on average furnace temperature

It is concluded that even though there is variation in the behaviour of furnace gas consumption and temperatures between steel qualities, it is not consistent enough to declare such variation as potential for reducing cost.

B.6 PRIMARY ROLLING MILL LOAD SHIFTING

The last initiative that was identified from literature is load shifting of the primary rolling mill. The evaluation of this initiative was conducted using a similar approach as the ladle furnace load shifting. There was, however, no energy consumption data available per occurrence as with the ladle furnace scheduling, and half-hourly power consumption data was used. The power consumption data was correlated with the steel qualities and profiles¹⁵ that were processed at the primary rolling mill at the same time. The average power consumption of different steel qualities and profile combinations were evaluated, with results as provided in Appendix G.

A frequency plot of the lowest (Steel Quality 73; Profile 21) and highest (Steel Quality 80; Profile 3) power consuming combinations is presented in Figure 77. This representation shows that there is an estimated variation of 2.2 MW between these combinations.

¹⁵ Steel profile names are withheld due to confidentiality (profiles are named *Profile 1* to *Profile 23*).

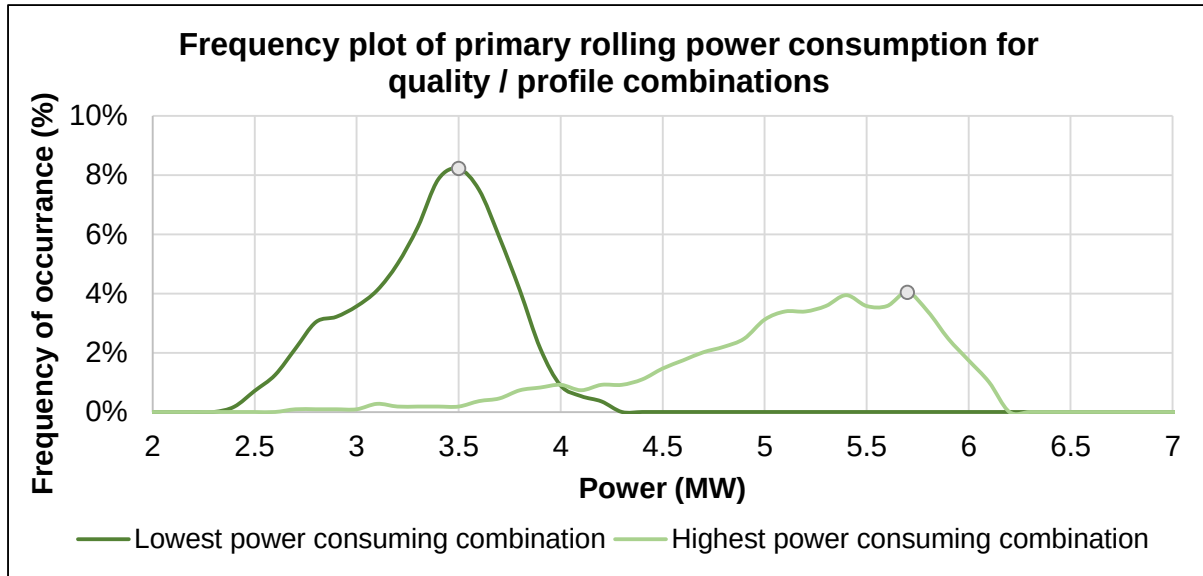


Figure 77: Frequency plot of highest and lowest power consuming combinations at the primary rolling mill

The theoretical maximum potential cost benefit was calculated using the same approach as for the ladle furnace load shifting evaluation and the winter TOU tariffs. The highest cost combination scenario is if the highest energy consuming combination is produced for one hour in peak time, and the lowest energy consuming combination is produced for one hour in off-peak time. The lowest cost combination scenario is if the lowest energy consuming combination is produced for one hour in peak time, and the highest energy consuming combination is produced for one hour in off-peak time. This is depicted by Figure 78, which indicates that the theoretical maximum potential cost benefit is R4 900. If this is the case for all five peak hours in a weekday, it translates to a potential cost saving of R24 500 per day.

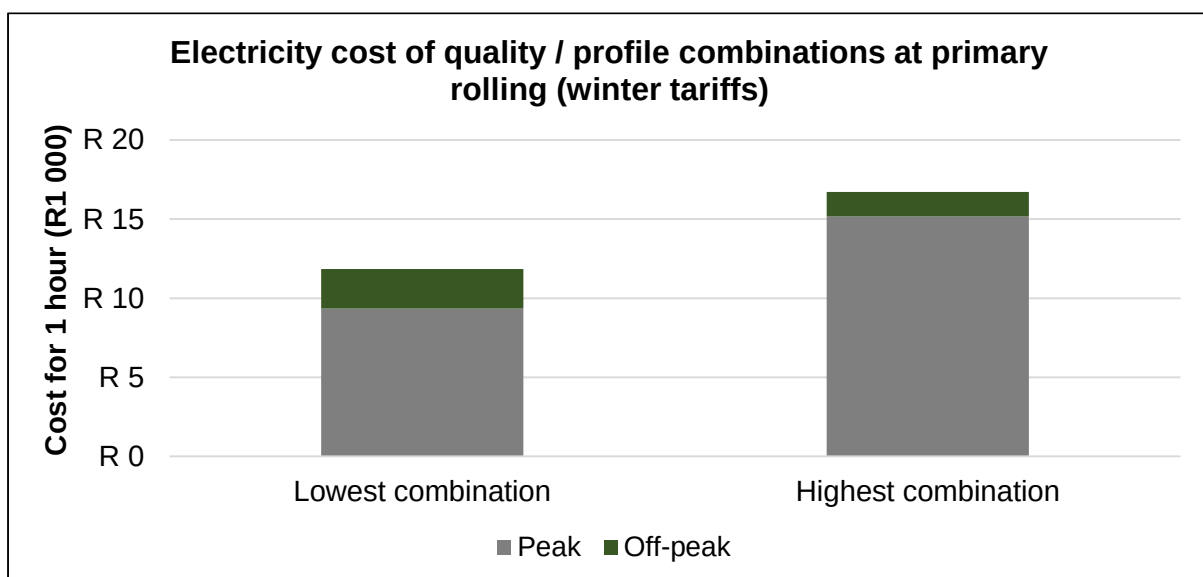


Figure 78: Highest and lowest electricity cost combinations at the primary rolling mill

It is concluded that there is a possible variation between scenarios to conduct a load shifting on the primary rolling mill. The theoretical maximum potential cost benefit is, however, less than that of the ladle furnace load shifting.

APPENDIX C: DESCRIPTION OF THE PROPERTIES OF STEEL QUALITIES

A list of steel quality properties is provided in Table 33, as used for the evaluation of several initiatives.

Table 33: Description of the properties of the steel qualities

Steel quality	General description	Al and Si content	Carbon content	Defect level
Quality 1	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: n/a	$0.0\% < C < 0.1\%$	Level 5
Quality 2	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: n/a	$0.0\% < C < 0.1\%$	Level 2
Quality 3	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: n/a	$0.1\% < C < 0.2\%$	Level 5
Quality 4	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: n/a	$0.1\% < C < 0.2\%$	Level 4
Quality 5	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: 0%	$0.1\% < C < 0.2\%$	Level 5
Quality 6	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: 0%	$0.1\% < C < 0.2\%$	Level 4
Quality 7	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: 0%	$0.2\% < C < 0.3\%$	Level 5
Quality 8	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: 0%	$0.2\% < C < 0.3\%$	Level 4
Quality 9	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: 0%	$0.3\% < C < 0.4\%$	Level 5
Quality 10	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: 0%	$0.3\% < C < 0.4\%$	Level 4
Quality 11	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: 0%	$0.4\% < C < 0.5\%$	Level 5
Quality 12	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: 0%	$0.4\% < C < 0.5\%$	Level 4
Quality 13	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: 0%	$0.5\% < C < 0.6\%$	Level 5
Quality 14	Plain carbon steel ($Mn \leq 1\%$)	Al: 0%; Si: 0%	$0.5\% < C < 0.6\%$	Level 4
Quality 15	Plain carbon steel ($Mn \leq 1\%$)	Al: n/a; Si: $\leq 0.15\%$	$0.0\% < C < 0.1\%$	Level 5
Quality 16	Plain carbon steel ($Mn \leq 1\%$)	Al: n/a; Si: $\leq 0.15\%$	$0.0\% < C < 0.1\%$	Level 4
Quality 17	Plain carbon steel ($Mn \leq 1\%$)	Al: n/a; $0.15\% < Si < 0.50\%$	$0.0\% < C < 0.1\%$	Level 5
Quality 18	Plain carbon steel ($Mn \leq 1\%$)	Al: n/a; $0.15\% < Si < 0.50\%$	$0.1\% < C < 0.2\%$	Level 5
Quality 19	Plain carbon steel ($Mn \leq 1\%$)	Al: n/a; $0.15\% < Si < 0.50\%$	$0.1\% < C < 0.2\%$	Level 4
Quality 20	Plain carbon steel ($Mn \leq 1\%$)	Al: n/a; $0.15\% < Si < 0.50\%$	$0.2\% < C < 0.3\%$	Level 5

Steel quality	General description	Al and Si content	Carbon content	Defect level
Quality 21	Plain carbon steel (Mn ≤ 1%)	Al: n/a; 0.15% < Si < 0.50%	0.3% < C < 0.4%	Level 4
Quality 22	Plain carbon steel (Mn ≤ 1%)	Al: n/a; 0.15% < Si < 0.50%	0.4% < C < 0.5%	Level 5
Quality 23	Plain carbon steel (Mn ≤ 1%)	Al: n/a; 0.15% < Si < 0.50%	0.5% < C < 0.6%	Level 5
Quality 24	Plain carbon steel (Mn ≤ 1%)	Al: n/a; 0.15% < Si < 0.50%	0.7% < C < 0.8%	Level 5
Quality 25	Plain carbon steel (Mn ≤ 1%)	Al: n/a; 0.15% < Si < 0.50%	0.9% < C < 1%	Level 5
Quality 26	Plain carbon steel (Mn ≤ 1%)	Al: n/a; 0.15% < Si < 0.50%	C > 1%	Level 5
Quality 27	Plain carbon steel (Mn > 1%)	Al: 0%; Si: 0%	0.1% < C < 0.2%	Level 5
Quality 28	Plain carbon steel (Mn > 1%)	Al: 0%; Si: 0%	0.2% < C < 0.3%	Level 5
Quality 29	Plain carbon steel (Mn > 1%)	Al: 0%; Si: 0%	0.2% < C < 0.3%	Level 4
Quality 30	Plain carbon steel (Mn > 1%)	Al: 0%; Si: 0%	0.4% < C < 0.5%	Level 5
Quality 31	Plain carbon steel (Mn > 1%)	Al: n/a; 0.15% < Si < 0.50%	0.2% < C < 0.3%	Level 5
Quality 32	Plain carbon steel (Mn > 1%)	Al: n/a; 0.15% < Si < 0.50%	0.5% < C < 0.6%	Level 5
Quality 33	Plain carbon steel (Mn > 1%)	Al: n/a; 0.15% < Si < 0.50%	0.7% < C < 0.8%	Level 5
Quality 34	Plain carbon steel (Mn > 1%)	Al: n/a; 0.15% < Si < 0.50%	C > 1%	Level 4
Quality 35	Niobium treated steel	Al: 0%; Si: 0%	0.1% < C < 0.2%	Level 5
Quality 36	Niobium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.1% < C < 0.2%	Level 5
Quality 37	Niobium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.2% < C < 0.3%	Level 5
Quality 38	Alloy steel	Al: 0%; Si: 0%	0.0% < C < 0.1%	Level 5
Quality 39	Alloy steel	Al: 0%; Si: 0%	0.1% < C < 0.2%	Level 5
Quality 40	Alloy steel	Al: 0%; Si: 0%	0.1% < C < 0.2%	Level 1
Quality 41	Alloy steel	Al: 0%; Si: 0%	0.2% < C < 0.3%	Level 5
Quality 42	Alloy steel	Al: 0%; Si: 0%	0.2% < C < 0.3%	Level 4
Quality 43	Alloy steel	Al: 0%; Si: 0%	0.2% < C < 0.3%	Level 1
Quality 44	Alloy steel	Al: 0%; Si: 0%	0.3% < C < 0.4%	Level 5
Quality 45	Alloy steel	Al: 0%; Si: 0%	0.3% < C < 0.4%	Level 4

Steel quality	General description	Al and Si content	Carbon content	Defect level
Quality 46	Alloy steel	Al: 0%; Si: 0%	0.3% < C < 0.4%	Level 2
Quality 47	Alloy steel	Al: 0%; Si: 0%	0.3% < C < 0.4%	Level 1
Quality 48	Alloy steel	Al: 0%; Si: 0%	0.4% < C < 0.5%	Level 5
Quality 49	Alloy steel	Al: 0%; Si: 0%	0.4% < C < 0.5%	Level 4
Quality 50	Alloy steel	Al: 0%; Si: 0%	0.4% < C < 0.5%	Level 2
Quality 51	Alloy steel	Al: 0%; Si: 0%	0.4% < C < 0.5%	Level 1
Quality 52	Alloy steel	Al: 0%; Si: 0%	0.5% < C < 0.6%	Level 4
Quality 53	Alloy steel	Al: 0%; Si: 0%	0.7% < C < 0.8%	Level 5
Quality 54	Alloy steel	Al: 0%; Si: 0%	0.7% < C < 0.8%	Level 4
Quality 55	Alloy steel	Al: 0%; Si: 0%	0.7% < C < 0.8%	Level 2
Quality 56	Alloy steel	Al: 0%; Si: 0%	0.9% < C < 1%	Level 5
Quality 57	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	0.1% < C < 0.2%	Level 5
Quality 58	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	0.3% < C < 0.4%	Level 5
Quality 59	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	0.3% < C < 0.4%	Level 4
Quality 60	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	0.4% < C < 0.5%	Level 4
Quality 61	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	0.5% < C < 0.6%	Level 5
Quality 62	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	0.5% < C < 0.6%	Level 4
Quality 63	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	0.7% < C < 0.8%	Level 5
Quality 64	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	0.7% < C < 0.8%	Level 4
Quality 65	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	0.9% < C < 1%	Level 5
Quality 66	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	C > 1%	Level 5
Quality 67	Alloy steel	Al: n/a; 0.15% < Si < 0.50%	C > 1%	Level 2
Quality 68	Alloy steel	Al: n/a; Si > 0.50%	0.0% < C < 0.1%	Level 5
Quality 69	Alloy steel	Al: n/a; Si > 0.50%	0.1% < C < 0.2%	Level 5
Quality 70	Alloy steel	Al: n/a; Si > 0.50%	0.5% < C < 0.6%	Level 4

Steel quality	General description	Al and Si content	Carbon content	Defect level
Quality 71	Alloy steel	Al: n/a; Si > 0.50%	0.7% < C < 0.8%	Level 5
Quality 72	Free cutting steel	Al: n/a; Si ≤ 0.15%	0.1% < C < 0.2%	Level 5
Quality 73	Vanadium treated steel	Al: 0%; Si: 0%	0.1% < C < 0.2%	Level 5
Quality 74	Vanadium treated steel	Al: 0%; Si: 0%	0.1% < C < 0.2%	Level 2
Quality 75	Vanadium treated steel	Al: 0%; Si: 0%	0.2% < C < 0.3%	Level 5
Quality 76	Vanadium treated steel	Al: n/a; Si ≤ 0.15%	0.0% < C < 0.1%	Level 5
Quality 77	Vanadium treated steel	Al: n/a; Si ≤ 0.15%	0.0% < C < 0.1%	Level 4
Quality 78	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.0% < C < 0.1%	Level 5
Quality 79	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.1% < C < 0.2%	Level 4
Quality 80	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.2% < C < 0.3%	Level 5
Quality 81	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.2% < C < 0.3%	Level 4
Quality 82	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.3% < C < 0.4%	Level 5
Quality 83	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.3% < C < 0.4%	Level 1
Quality 84	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.4% < C < 0.5%	Level 5
Quality 85	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.4% < C < 0.5%	Level 4
Quality 86	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.5% < C < 0.6%	Level 4
Quality 87	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.7% < C < 0.8%	Level 5
Quality 88	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	0.9% < C < 1%	Level 5
Quality 89	Vanadium treated steel	Al: n/a; 0.15% < Si < 0.50%	C > 1%	Level 5
Quality 90	Vanadium treated steel	Al: n/a; Si > 0.50%	C > 1%	Level 5

APPENDIX D: ENERGY INTENSITY OF STEEL QUALITIES AT LADLE FURNACES

A list of the energy intensities of Production Route 2 steel qualities processed at the ladle furnaces is provided in Table 34, as calculated according to the discussion of Section B.3.

Table 34: Energy intensity of Production Route 2 steel qualities at the ladle furnaces

Steel quality	Energy consumption (kWh/heat)
Quality 1	4 688
Quality 3	5 367
Quality 5	4 214
Quality 15	4 859
Quality 16	3 610
Quality 17	4 394
Quality 18	3 953
Quality 19	3 656
Quality 20	3 947
Quality 21	4 016
Quality 22	4 605
Quality 23	4 503
Quality 24	3 878
Quality 25	4 480
Quality 26	4 466
Quality 27	4 282
Quality 31	4 477
Quality 35	4 343
Quality 36	4 603
Quality 37	4 542
Quality 41	5 484
Quality 42	4 894
Quality 44	4 837
Quality 46	4 316
Quality 66	4 729
Quality 72	4 770
Quality 73	4 144
Quality 75	4 993
Quality 76	4 460
Quality 78	3 968
Quality 80	4 792
Quality 81	4 316
Quality 85	3 824
Quality 87	4 490
Quality 88	4 605

A list of the energy intensities of Production Route 3 steel qualities processed at the ladle furnaces is provided in Table 35, as calculated according to the discussion of Section A.3.

Table 35: Energy intensity of Production Route 3 steel qualities at the ladle furnaces

Steel quality	Energy consumption (kWh/heat)
Quality 5	4 700
Quality 11	6 641
Quality 13	6 476
Quality 19	8 802
Quality 22	6 596
Quality 26	7 770
Quality 39	8 706
Quality 43	7 869
Quality 47	10 203
Quality 48	8 534
Quality 49	8 150
Quality 51	8 539
Quality 53	7 449
Quality 55	8 689
Quality 58	10 373
Quality 63	8 574
Quality 67	7 807
Quality 70	8 182
Quality 71	7 681
Quality 84	9 666
Quality 85	8 427

APPENDIX E: LADLE AND CRANE TIME LOSS REDUCTION REGRESSION MODELS

In order to determine the effect of a reduction in transfer time in Section B.4, it was attempted to quantify the loss in steel temperature and increased energy consumption at the ladle furnaces due to time losses. These regression models, however, show that the increased transfer times do not have a clear effect on the temperature or energy consumption. A regression model of the ladle furnace-concast transfer time versus temperature reduction is presented in Figure 79.

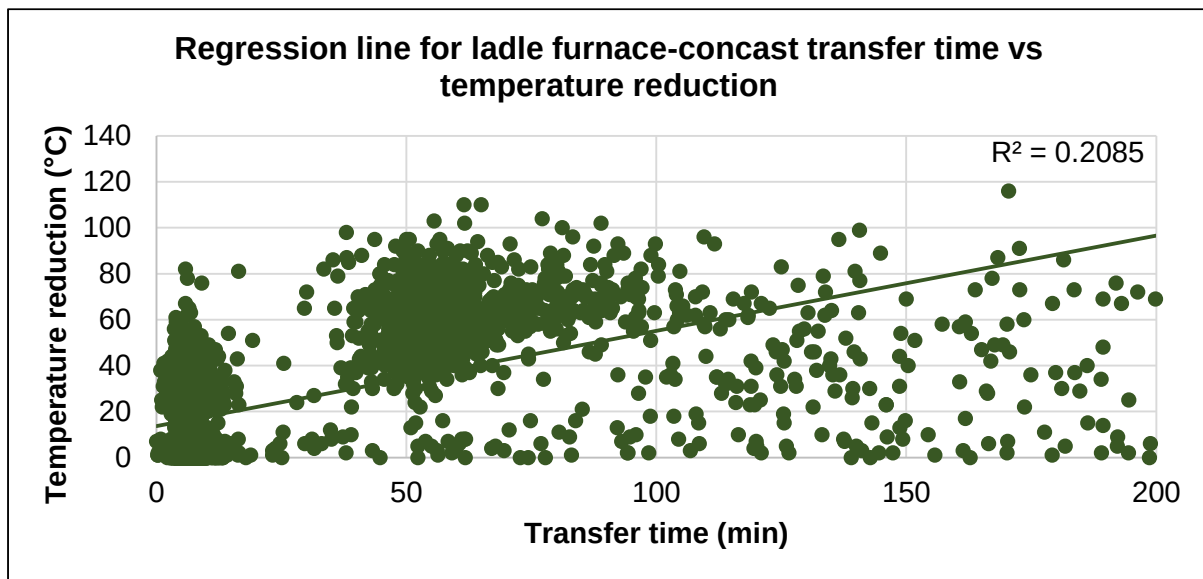


Figure 79: Ladle furnace-concast transfer time vs temperature reduction regression

A regression model of the BOF-ladle furnace transfer time versus temperature reduction is presented in Figure 80.

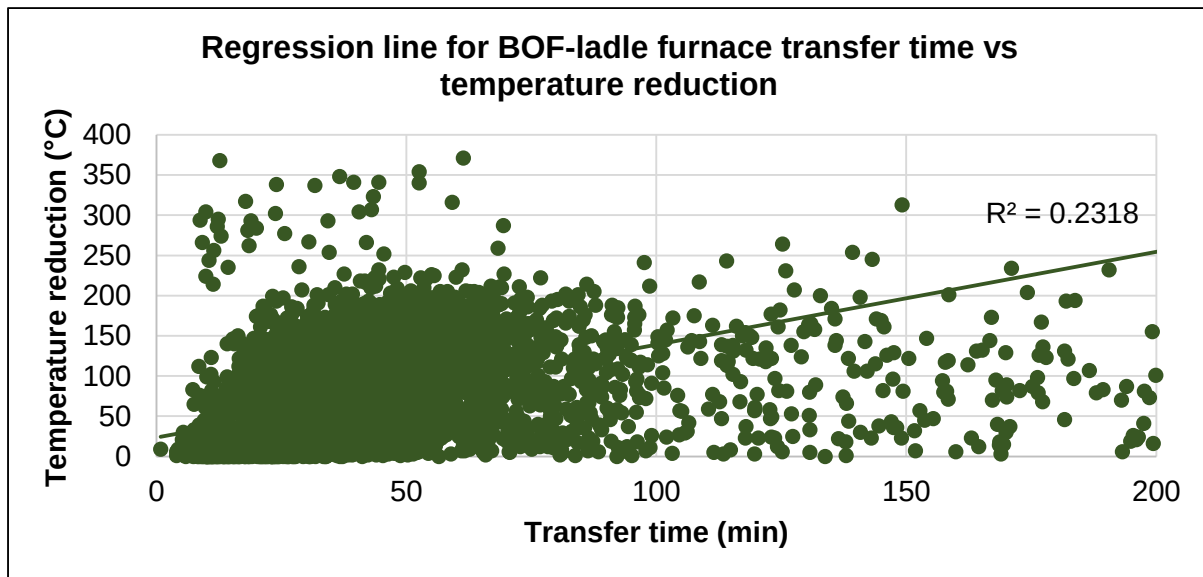


Figure 80: BOF-concast transfer time vs temperature reduction regression

A regression model of the BOF-ladle furnace transfer time versus ladle furnace energy consumption is presented in Figure 81.

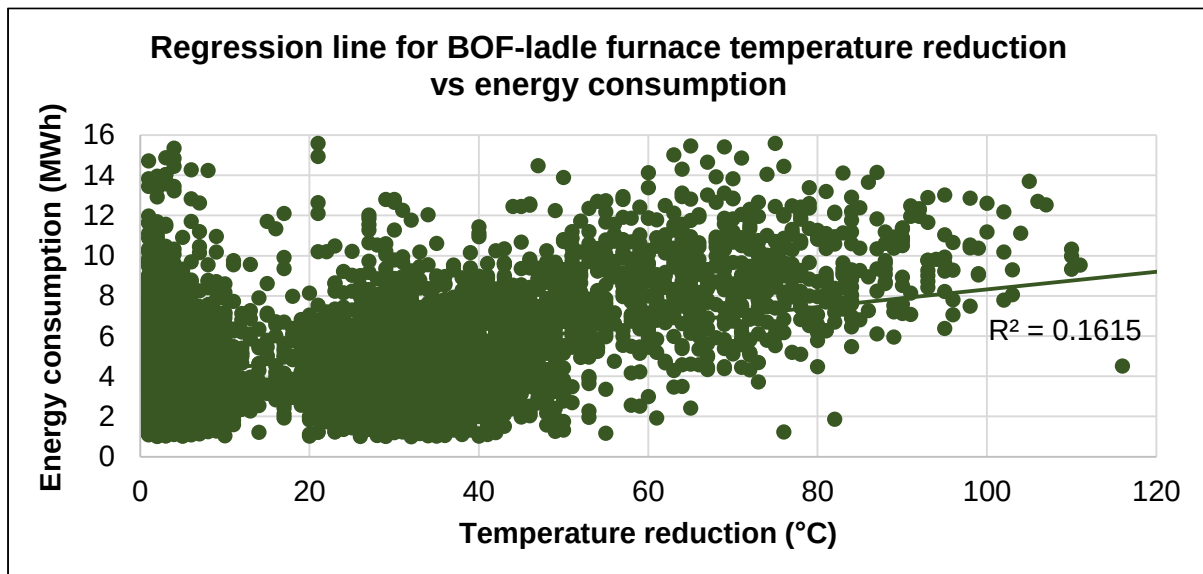


Figure 81: BOF-concast transfer time vs energy consumption regression

APPENDIX F: VARIANCE OF APPORTIONMENT MODEL STEEL QUALITY PROPERTIES

Several properties of steel qualities relevant to the primary rolling mill furnace apportionment model discussed in Section B.5 are provided in Table 36.

Table 36: Variance in the properties of the apportionment model steel qualities

Steel quality	Temperature (°C)	Gas consumption (m ³ /h)	Intensity (m ³ /h/°C)	Count
Quality 4	1 267	7 583	5.99	3
Quality 5	1 255	6 308	5.03	56
Quality 15	1 254	10 662	8.51	6
Quality 17	1 248	8 574	6.87	156
Quality 18	1 252	8 834	7.05	22
Quality 19	1 265	10 333	8.17	7
Quality 20	1 248	8 366	6.70	166
Quality 21	1 264	8 223	6.51	10
Quality 22	1 259	8 801	6.99	7
Quality 23	1 262	8 680	6.88	2
Quality 24	1 269	8 979	7.08	19
Quality 25	1 247	7 665	6.15	8
Quality 26	1 254	8 199	6.54	3
Quality 31	1 231	7 143	5.80	21
Quality 34	1 266	8 402	6.64	2
Quality 35	1 249	7 897	6.32	8
Quality 36	1 266	9 907	7.82	16
Quality 37	1 257	8 797	7.00	18
Quality 42	1 255	9 442	7.52	12
Quality 45	1 139	5 796	5.09	4
Quality 46	1 251	9 589	7.67	5
Quality 65	1 270	9 737	7.67	1
Quality 66	1 241	8 431	6.79	9
Quality 69	1 280	4 641	3.63	1
Quality 73	1 247	6 769	5.43	55
Quality 76	1 185	7 436	6.27	6
Quality 80	1 270	7 890	6.21	27
Quality 82	1 240	4 513	3.64	2
Quality 87	1 265	10 794	8.54	8
Quality 88	1 197	5 067	4.23	2

APPENDIX G: PRIMARY ROLLING MILL ELECTRICAL ENERGY INTENSITY

The average power consumption of different steel qualities and profile combinations is provided in Table 37, as determined from the discussion in Section B.6.

Table 37: Electrical energy intensities for the primary rolling mill

Power consumption (kW)	Profile 2	Profile 3	Profile 6	Profile 7	Profile 10	Profile 14	Profile 15	Profile 16	Profile 17	Profile 21
Quality 4	–	–	–	–	–	–	4 452	–	–	–
Quality 5	–	–	–	–	–	–	–	4 000	–	3 559
Quality 6	–	–	–	–	–	–	–	–	4 488	–
Quality 12	–	–	–	–	–	–	–	–	4 623	–
Quality 13	–	–	–	–	–	–	–	–	4 558	–
Quality 15	–	–	4 906	–	–	–	4 849	–	–	–
Quality 16	–	–	–	–	4 984	–	–	–	–	–
Quality 17	–	5 307	4 878	–	–	–	4 799	–	–	–
Quality 18	–	–	–	–	–	–	4 736	–	–	–
Quality 19	–	–	–	–	–	–	4 661	–	–	–
Quality 20	4 437	5 410	–	4 650	–	–	4 798	–	4 853	–
Quality 21	–	–	–	–	–	–	4 733	–	–	–
Quality 22	–	–	–	–	–	–	4 838	–	–	–
Quality 23	–	–	–	–	–	–	4 294	–	–	–
Quality 24	–	–	–	–	–	–	4 779	–	–	–
Quality 25	–	–	–	–	–	–	4 823	–	–	–
Quality 26	–	–	4 811	–	–	–	4 825	–	–	–
Quality 31	–	–	–	4 873	–	–	4 513	–	–	–

Power consumption (kW)	Profile 2	Profile 3	Profile 6	Profile 7	Profile 10	Profile 14	Profile 15	Profile 16	Profile 17	Profile 21
Quality 35	–	–	–	4 782	–	–	–	–	4 761	–
Quality 36	–	5 437	–	–	–	4 074	5 067	–	–	–
Quality 37	–	–	–	–	–	–	5 022	–	–	–
Quality 41	–	–	–	–	–	–	–	3 696	–	–
Quality 42	–	–	4 884	–	–	–	4 821	–	4 784	–
Quality 45	–	–	–	–	–	–	4 845	–	4 801	–
Quality 47	–	–	–	–	–	–	–	–	4 398	–
Quality 49	–	–	–	–	–	–	–	–	4 972	–
Quality 55	–	–	–	–	–	–	5 153	–	–	–
Quality 63	–	–	–	–	–	–	–	–	4 590	–
Quality 66	–	–	–	–	–	–	4 880	–	–	–
Quality 70	–	–	–	–	–	–	5 179	–	4 666	–
Quality 73	–	–	–	–	–	–	–	3 864	–	3 354
Quality 76	–	–	5 075	–	–	–	5 141	–	–	–
Quality 80	–	5 440	–	–	4 721	–	4 991	–	–	–
Quality 81	–	–	–	–	–	–	–	–	4 515	–
Quality 85	–	–	–	–	–	–	–	–	4 604	–
Quality 87	–	–	–	–	–	–	4 796	–	–	–
Quality 88	–	–	–	–	–	–	4 881	–	–	–

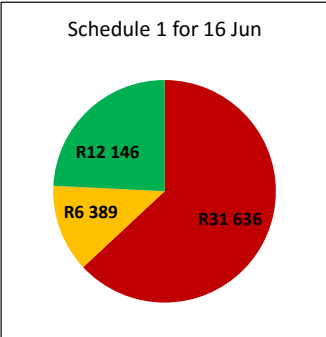
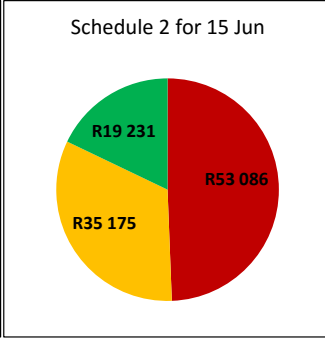
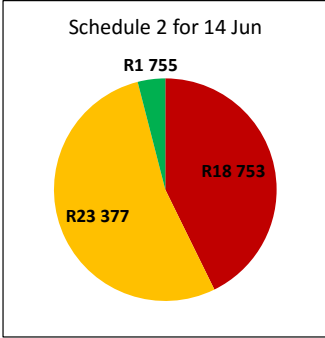
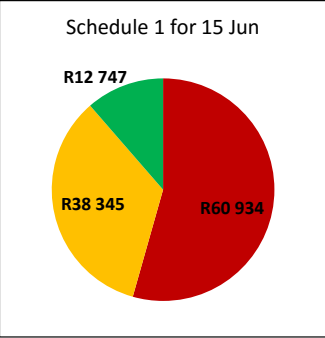
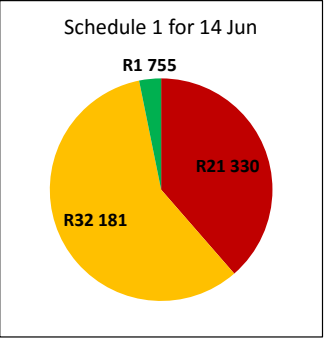
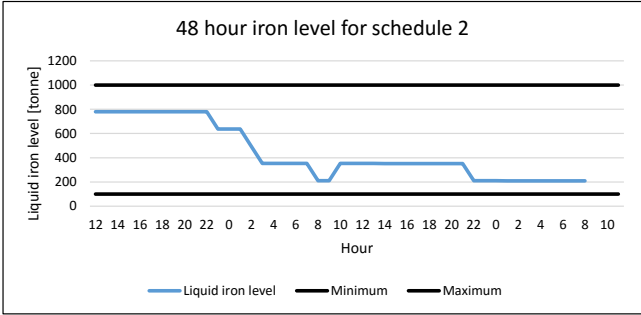
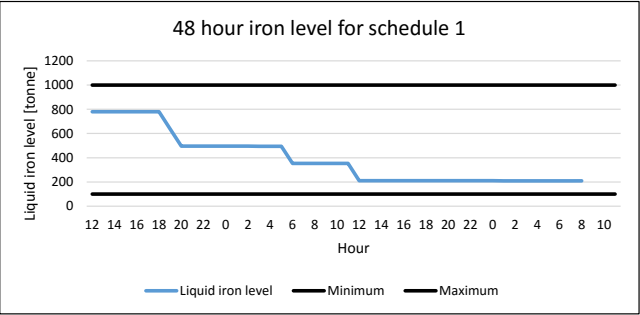
APPENDIX H: LADLE FURNACE LOAD SHIFTING IMPLEMENTATION

H.1 SIMPLIFIED ONLINE INTERFACE

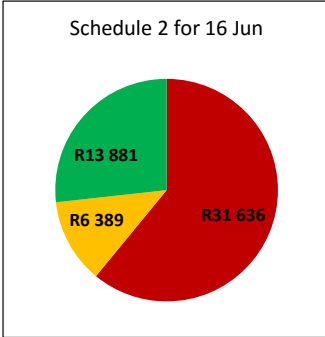
Appendix H.1 presents the conceptual view that was used to develop the online interface for the ladle furnace load shifting implementation, as discussed in Step I.1 of Section 5.2.5. This is presented on the next page.

Inputs		
Blast furnace production rate	3400	t/day
Current liquid iron level	780	t

Cost comparison for different schedules											
Schedule 1						Schedule 2					
Casting time		Ladle furnace 1		Ladle furnace 2		Liquid iron		Casting time		Ladle furnace 1	
Date	Hour	Steel grade	Route	Steel grade	Route	level [tonne]		Date	Hour	Steel grade	Route
2017/06/14	12					780		2017/06/14	12		
2017/06/14	13			Example 2	2	780		2017/06/14	13	Example 3	2
2017/06/14	14			Example 2	2	780		2017/06/14	14	Example 3	2
2017/06/14	15			Example 2	2	780		2017/06/14	15	Example 3	2
2017/06/14	16			Example 2	2	780		2017/06/14	16	Example 3	2
2017/06/14	17			Example 2	2	780		2017/06/14	17	Example 3	2
2017/06/14	18			Example 2	2	780		2017/06/14	18	Example 3	2
2017/06/14	19			Example 2	2	638		2017/06/14	19	Example 3	2
2017/06/14	20			Example 2	2	496		2017/06/14	20	Example 3	2
2017/06/14	21	Example 1	2	Example 2	2	496		2017/06/14	21		
2017/06/14	22	Example 1	2	Example 2	2	496		2017/06/14	22		
2017/06/14	23			Example 2	2	496		2017/06/14	23	Example 2	2
2017/06/15	0			Example 2	2	496		2017/06/15	0	Example 2	2
2017/06/15	1	Example 3	2			495		2017/06/15	1	Example 2	2
2017/06/15	2	Example 3	2			495		2017/06/15	2	Example 2	2
2017/06/15	3	Example 3	2			495		2017/06/15	3	Example 2	2
2017/06/15	4	Example 3	2			495		2017/06/15	4	Example 2	2
2017/06/15	5	Example 3	2			495		2017/06/15	5	Example 2	2
2017/06/15	6	Example 3	2			353		2017/06/15	6	Example 2	2
2017/06/15	7	Example 3	2			353		2017/06/15	7	Example 2	2
2017/06/15	8	Example 3	2	Example 4	2	353		2017/06/15	8	Example 2	2
2017/06/15	9			Example 4	2	353		2017/06/15	9	Example 2	2
2017/06/15	10			Example 4	2	353		2017/06/15	10	Example 2	2
2017/06/15	11			Example 4	2	353		2017/06/15	11		
2017/06/15	12			Example 4	2	211		2017/06/15	12		
2017/06/15	13			Example 4	2	211		2017/06/15	13	Example 4	2
2017/06/15	14	Example 5	2	Example 4	2	211		2017/06/15	14	Example 4	2
2017/06/15	15			Example 4	2	211		2017/06/15	15	Example 4	2
2017/06/15	16			Example 4	2	211		2017/06/15	16	Example 4	2
2017/06/15	17			Example 4	2	211		2017/06/15	17	Example 4	2
2017/06/15	18			Example 4	2	210		2017/06/15	18	Example 4	2
2017/06/15	19			Example 4	2	210		2017/06/15	19	Example 4	2
2017/06/15	20	Example 5	2			210		2017/06/15	20	Example 4	2
2017/06/15	21	Example 5	2			210		2017/06/15	21	Example 4	2
2017/06/15	22			Example 4	2	210		2017/06/15	22	Example 4	2
2017/06/15	23			Example 4	2	210		2017/06/15	23	Example 4	2
2017/06/16	0			Example 4	2	210		2017/06/16	0	Example 4	2
2017/06/16	1			Example 4	2	210		2017/06/16	1		
2017/06/16	2			Example 4	2	210		2017/06/16	2		
2017/06/16	3			Example 4	2	210		2017/06/16	3		
2017/06/16	4			Example 4	2	210		2017/06/16	4		
2017/06/16	5			Example 4	2	210		2017/06/16	5		
2017/06/16	6			Example 4	2	209		2017/06/16	6		
2017/06/16	7			Example 4	2	209		2017/06/16	7		
2017/06/16	8			Example 4	2	209		2017/06/16	8		
2017/06/16	9			Example 4	2			2017/06/16	9		
2017/06/16	10	Example 1	2					2017/06/16	10		
2017/06/16	11	Example 1	2					2017/06/16	11		



Total cost	
2017/06/14	R55 266
2017/06/15	R112 026
2017/06/16	R50 171
Total	R217 463



Total cost	
2017/06/14	R43 885
2017/06/15	R107 492
2017/06/16	R51 906
Total	R203 283

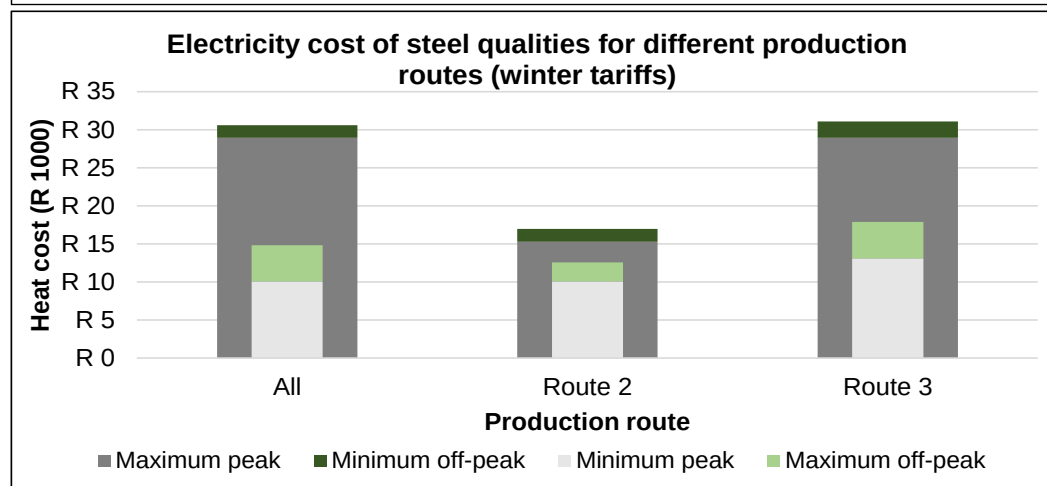
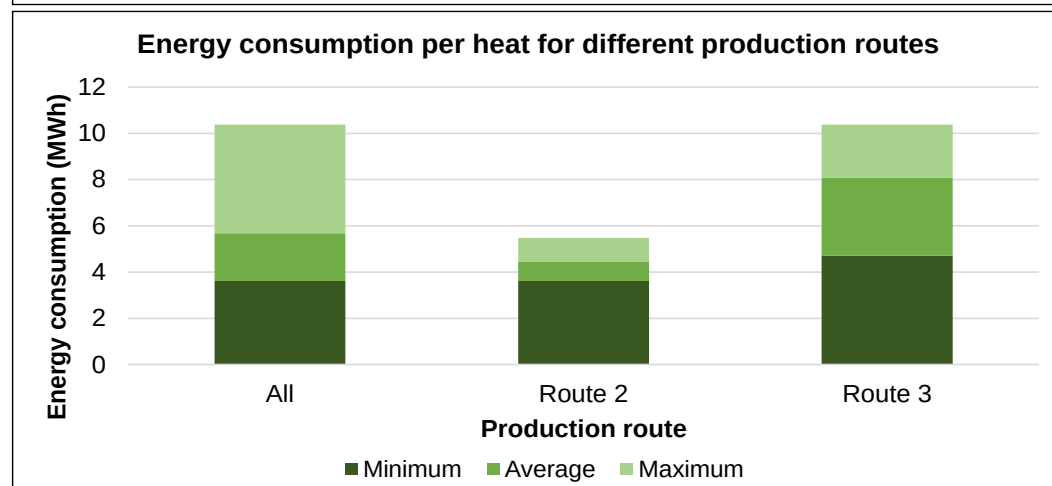
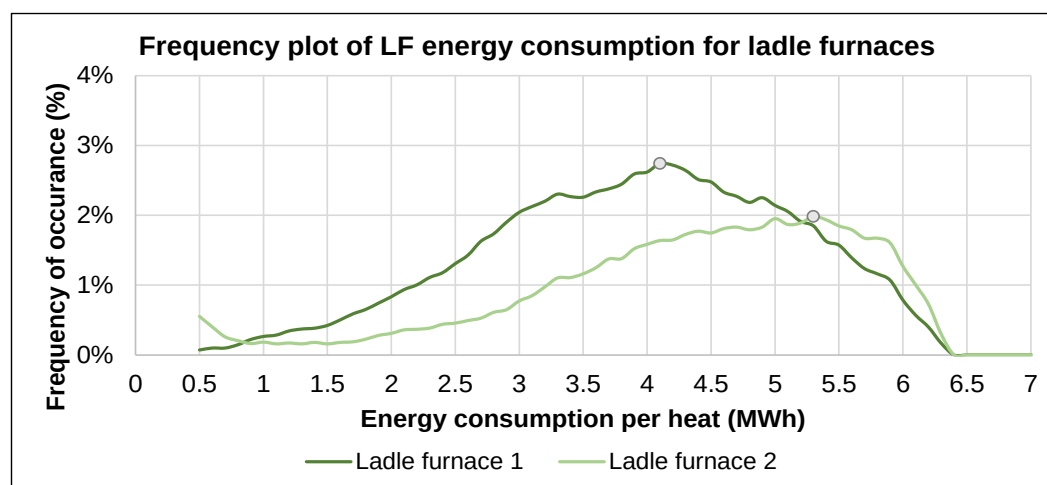
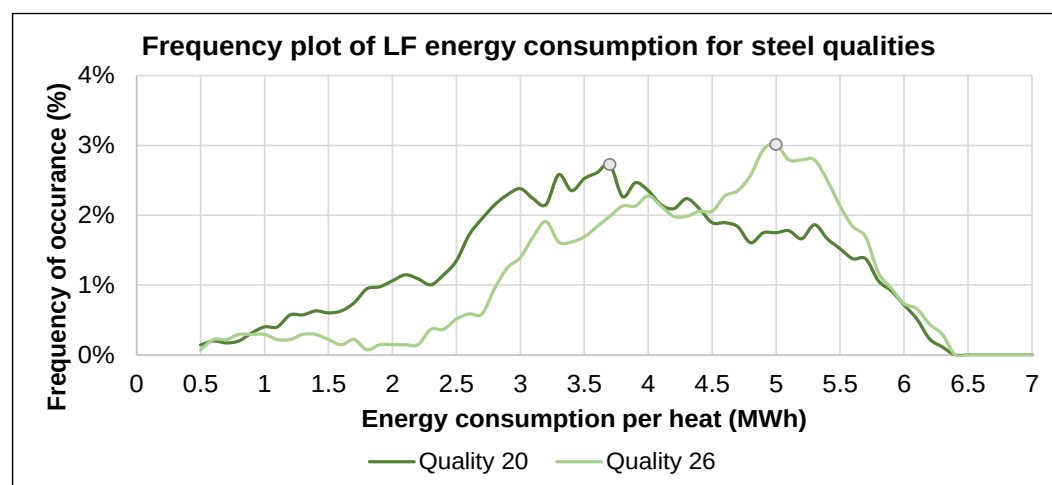
H.2 LADLE FURNACE LOAD SHIFTING INFORMATION SHEET

Appendix H.1 presents the information sheet that was used to create awareness and highlight benefits for the ladle furnace load shifting implementation in Step I.2 of Section 5.2.5. This is presented on the next page.

Potential benefits of ladle furnace load shift

Max. cost benefit	Per heat	Per day	Per week
Route 2	R4 500	R22 500	R112 500
Route 3	R13 200	R66 000	R330 000

Use both casters during off-peak time to lower liquid iron level before peak time.
Schedule only one ladle furnace in peak times if possible.
Only change BOF tap holes during peak times.



H.3 LADLE FURNACE LOAD SHIFTING FLAG REPORT

Appendix H.3 presents the ladle furnace load shifting flag report used during the implementation in Step I.3 of Section 5.2.5. This is presented on the next page.

Ladle furnace load shift: Flag report for 5 Jul '17

Five highest energy consuming steel qualities

Steel quality	Prefered period
Quality 39	
Quality 39	
Quality 39	
Quality 39	
Quality 39	

It is suggested to produce these steel qualities out of peak time.

Five lowest energy consuming steel qualities

Steel quality	Prefered period
Quality 20	
Quality 20	
Quality 20	
Quality 20	
Quality 27	

These steel qualities are safe for peak time production.*

Potential cost benefit of performing load shift on 5 Jul '17
R60 000

**If possible, do not use ladle furnaces at all during peak times.*

Guidelines for ladle furnace load shift
Use both casters during off-peak time to lower liquid iron level before peak time.
Schedule only one ladle furnace in peak times if possible.
Only change BOF tap holes during peak times.

TOU tariff times			
Hour	Weekday	Saturday	Sunday
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			

Relevant steel qualities in order of electrical energy consumption

Steel quality list		
Peak preferred	Peak safe	Critical non-peak
Quality 20	Quality 37	Quality 80
Quality 27		Quality 15
		Quality 42
		Quality 39

H.4 LADLE FURNACE LOAD SHIFTING IMPLEMENTATION STEPS

Table 38 presents a basic list of practical tasks conducted during the ladle furnace load shifting implementation as referred to in Step I.4 of Section 5.2.5.

Table 38: Basic list of tasks conducted during ladle furnace load shifting implementation

Task
Spend time in the ladle furnace control rooms to evaluate project feasibility and practical constraints.
Spend time in the concast control room (with schedulers) to determine project feasibility and practical constraints.
Discuss project feasibility and practical constraints with plant manager.
Discuss project feasibility and practical constraints with senior planner.
Include TOU colours on senior production planner's priority list.
Have discussions with concast schedulers (coordinators) to analyse constraints and determine solutions.
Discuss feasibility and possible solutions with relevant steel plant personnel (metallurgists).
Send emails to production planner to suggest schedule changes and determine flexibility of priority list.
Send email to steel plant personnel regarding practical steps to reduce peak time consumption.
Set up data acquisition procedures to be able to monitor and assess the initiative.
Calculate possible cost benefit.
Discuss and iterate steel quality energy intensity database with different parties.
Spend time with schedulers to implement steel quality energy intensity database.
Provide a printed and laminated steel quality energy intensity database to planners and ladle furnace control room operators.
Spend time in the concast control room (with schedulers) to determine inputs for online interface and make suggestions during scheduling.
Generate and send feedback reports.
Provide TOU clocks in the concast and ladle furnace control rooms.
Develop and implement the online interface to compare various scheduling scenarios.
Investigate baseline options.

APPENDIX I: HOT CHARGING IMPLEMENTATION

I.1 SIMPLIFIED ONLINE INTERFACE

Appendix I.1 presents a conceptual view of the online interface for the hot charging implementation, as discussed in Step I.1 of Section 5.2.5. This is presented on the next page.

Priority	Quality	Profile	Number of casts	Quality scheduled at concast			Scheduled for hot charging			Feedback
1	Example 1	Example A	3		✓			X		Missed opportunity
2	Example 2	Example A	2		X			X		n/a
3	Example 3	Example A	2		X			X		n/a
4	Example 2	Example B	4		X			X		n/a
5	Example 4	Example B	6		✓			✓		Good
6	Example 5	Example A	2		X			X		n/a
7	Example 5	Example A	2		X			X		n/a
8	Example 6	Example C	8		✓			X		Missed opportunity
9	Example 7	Example C	2		✓			✓		Good
10	Example 6	Example D	4		✓			✓		Good
11										
12										
13										
14										
15										

Planned outputs		
Production	5 600	tonne
Hot charging	1 920	tonne
Hot charging	34%	
Theoretical cost benefit	R32 249	

Potential outputs		
Hot charging	3 680	tonne
Hot charging	66%	
Potential cost benefit	R43 782	

Missed opportunities		
Hot charging	1 760	tonne
Hot charging	31%	
<40% hot charging	R0	
<66% hot charging	R11 533	

I.2 HOT CHARGING INFORMATION SHEET

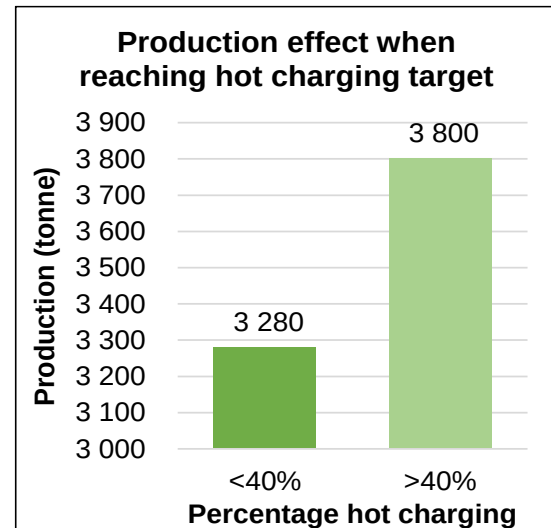
Appendix I.2 presents the information sheet and presentation used to create awareness and highlight benefits for the hot charging implementation, as discussed in Step I.2 of Section 5.2.5. This is presented on the next page.

Possible benefits of increased hot charging

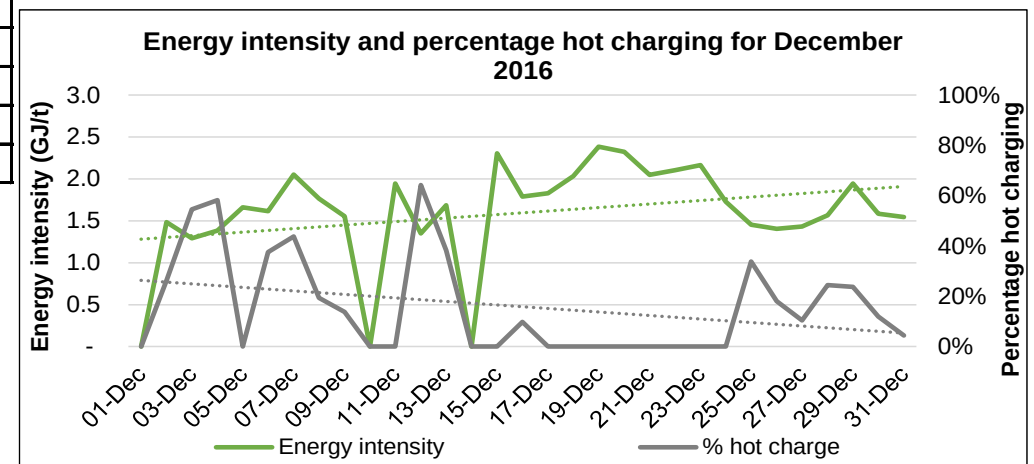
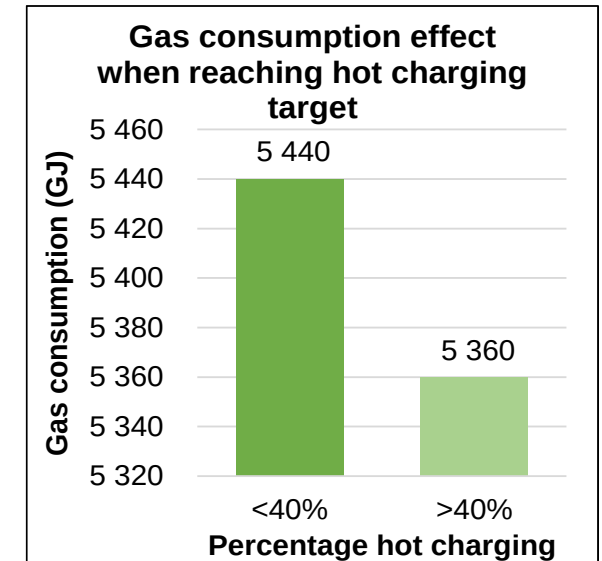
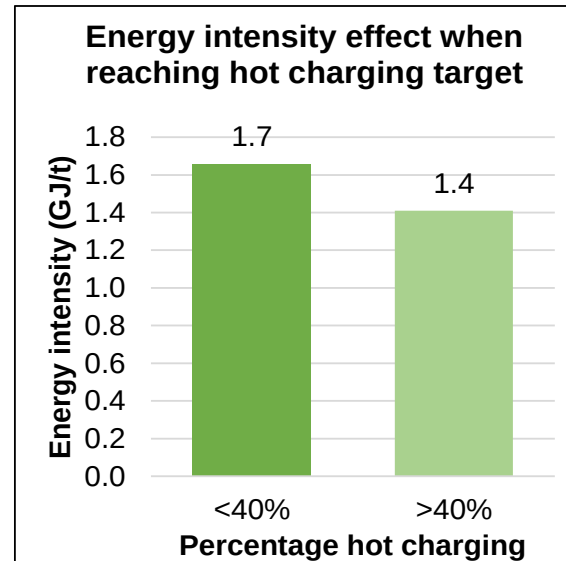
Data analysed	1 January 2016 - 31 December 2016
---------------	-----------------------------------

Assessment period values			
Description	Production [t]	Hot charge [t]	Hot charge [%]
Total	1 193 110	322 471	27%

Theoretical energy cost benefit*			
Range (±10%)	Cost benefit (R/day)		Cost benefit (R/year)
10%	R	-	R -
30%	R	32 249	R 10 061 688
50%	R	43 782	R 13 659 984
70%	R	47 458	R 14 806 896
90%	R	79 861	R 24 916 632



Production benefit	
Direct loading	Production [t/day]
Below target [<40%]	3 280
Above target [>40%]	3 800
Production increase	520



*Assume 1 day maintenance per week

PRIMARY ROLLING MILL FURNACE: INCREASED HOT CHARGING

Benefits and suggested action plan

BACKGROUND

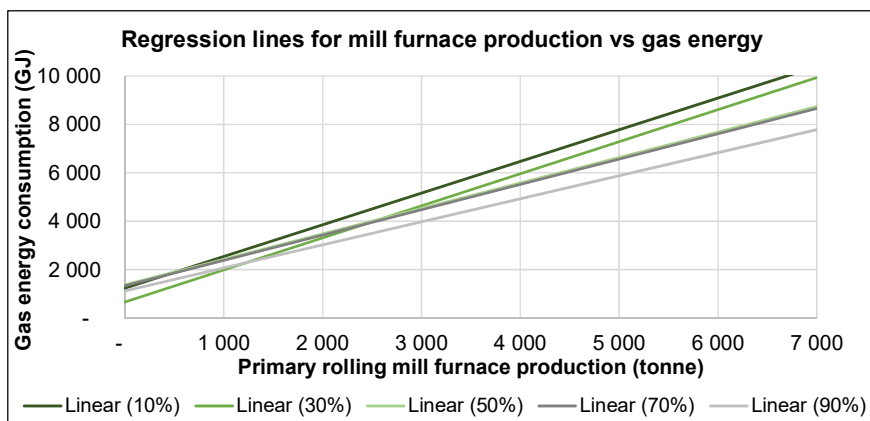
- Hot charging of blooms into primary rolling mill furnace is possible
- Infrastructure, equipment and personnel in place
- Past 12 months: 27% of blooms were direct loaded
- Targeted direct loading: 40%
- Aim to increase % direct loading

DATA ANALYSIS

- Data from 1 Jan 2016 to 31 Dec 2016 were analysed

Year-to-date values			
Description	Production [t]	Direct load [t]	Direct load [%]
Total	1 193 110	322 471	27%

VARIATION IN ENERGY CONSUMPTION



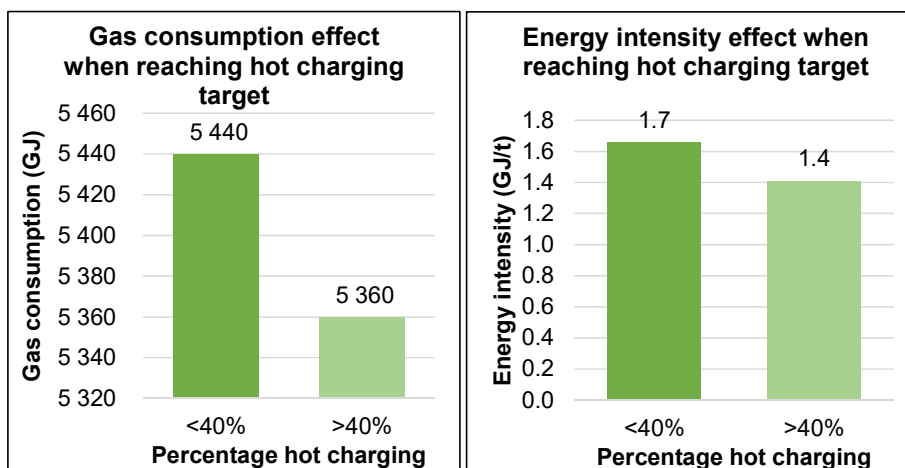
POSSIBLE PRODUCTION BENEFITS

- Possible production benefits of reaching target

Production benefit	
Direct loading	Production [t/day]
Below target [<40%]	3 280
Above target [>40%]	3 800
Production increase	520

- Increased production of 520 t/day

POSSIBLE ENERGY CONSUMPTION BENEFITS



POSSIBLE ENERGY COST BENEFITS

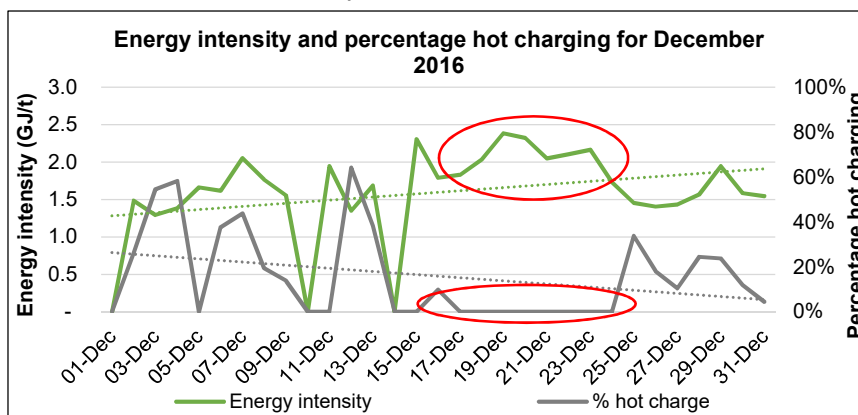
Possible energy cost saving of R13.7-million per year if hot charging % > 40%

Theoretical energy cost benefit*			
Range ($\pm 10\%$)	Cost benefit (R/day)		Cost benefit (R/year)
10%	R	-	R -
30%	R	32 249	R 10 061 688
50%	R	43 782	R 13 659 984
70%	R	47 458	R 14 806 896
90%	R	79 861	R 24 916 632

*Assume 1 day maintenance per week

POSSIBLE ENERGY COST BENEFITS

Comparison of % direct loading and cost intensity for December 2016 *[Example of effect]*



SUGGESTED ACTION PLAN

1. Kick-off meetings with schedulers and primary rolling mill
2. System to be used by planners
 - i. Comparing concast and primary rolling mill planning
 - ii. Flagging direct load opportunities
3. Perform a shift-long test
4. Cold casts between hot casts *[2 x hot + 1 x cold + 2 x hot + ...]*
5. Providing more information to mills
6. Evaluate direct load performance
7. Evaluate billet stock size

I.3 HOT CHARGING FLAG REPORT

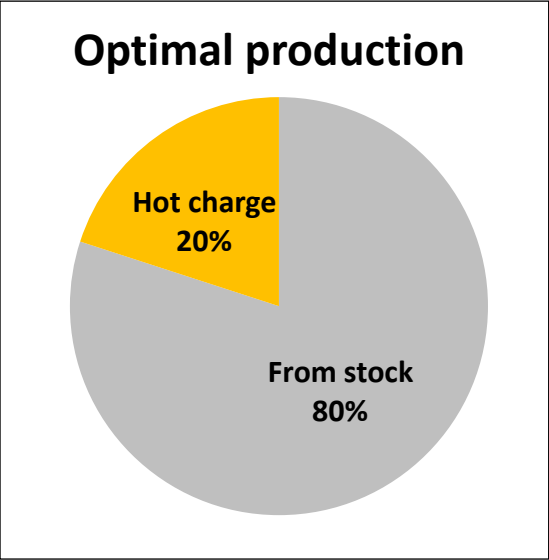
Appendix I.3 presents the hot charging flag report used during the implementation in Step I.3 of Section 5.2.5. This is presented on the next page.

1. Hot charging opportunities for 10 Apr '17

[illegible]

2. Potential benefit of maximum hot charging

Potential hot charging benefits for 10 Apr '17	
Percentage hot charging	20%
Energy cost reduction	R8 000



Day of the week	TOU tariffs																							
Sunday																								
Saturday																								
Weekdays																								
Hour of the day	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

I.4 HOT CHARGING IMPLEMENTATION STEPS

Table 39 presents a basic list of practical tasks conducted during the ladle furnace load shifting implementation, as referred to in Step I.4 of Section 5.2.5.

Table 39: Basic list of tasks conducted during hot charging initiative implementation

Task
Spend time in control rooms to evaluate project feasibility and practical constraints.
Discuss project feasibility and practical constraints with plant and operations managers.
Discuss project feasibility and practical constraints with senior planner.
Have kick-off meetings with different parties (production shifts, control room operators, plant management, production planners, etc.).
Discuss possible interactive effects of initiatives with steel plant personnel.
Distribute flagging reports based on received production plans.
Generate and send feedback reports.
Set up data acquisition procedures to be able to monitor and assess the initiative.
Calculate possible cost benefit.
Generate and send feedback reports.
Develop and implement the online interface.
Investigate baseline options.

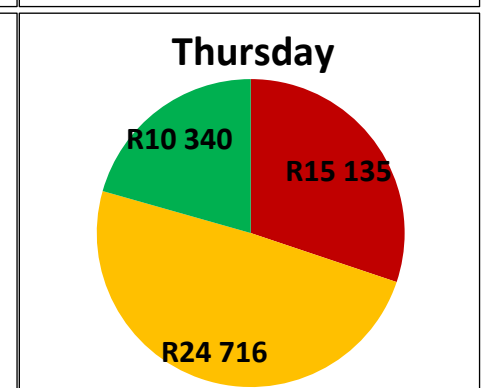
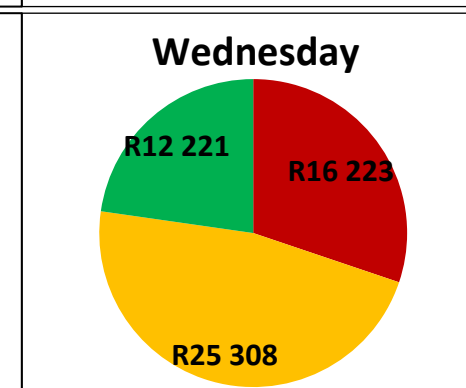
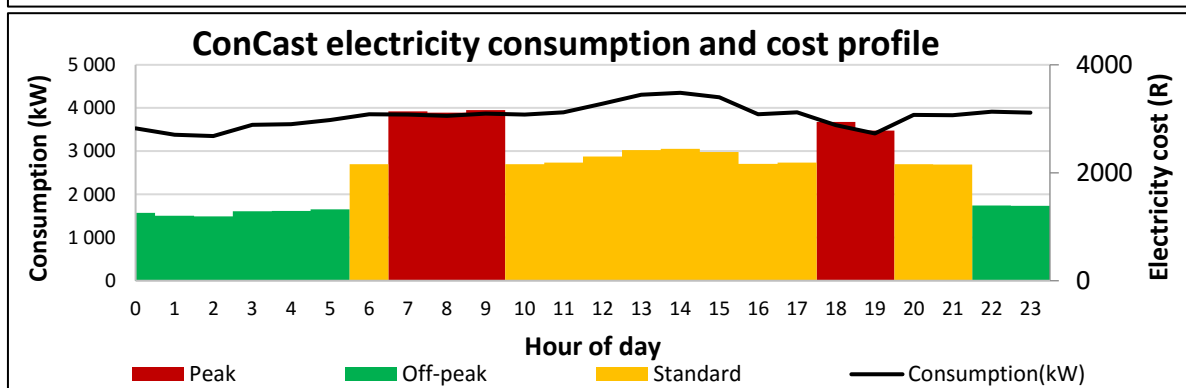
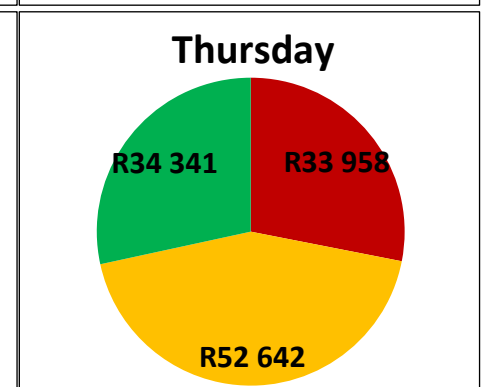
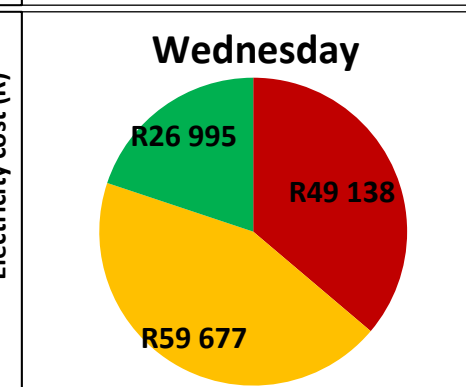
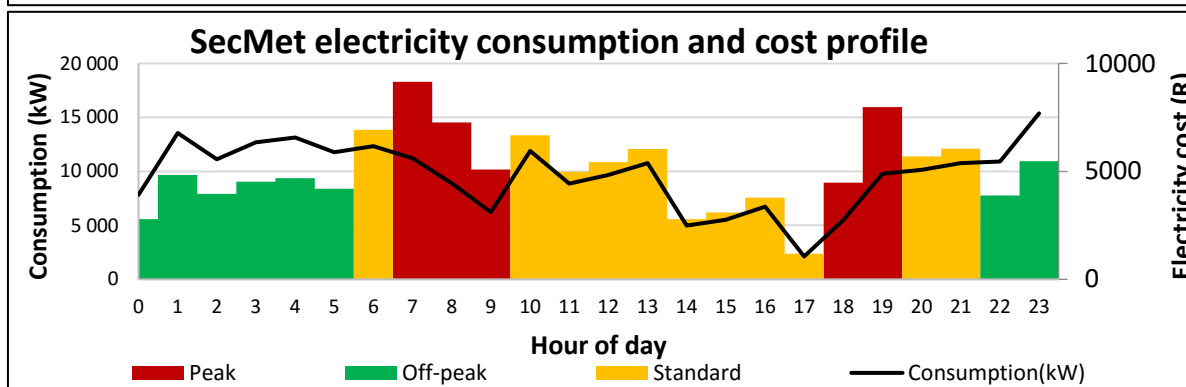
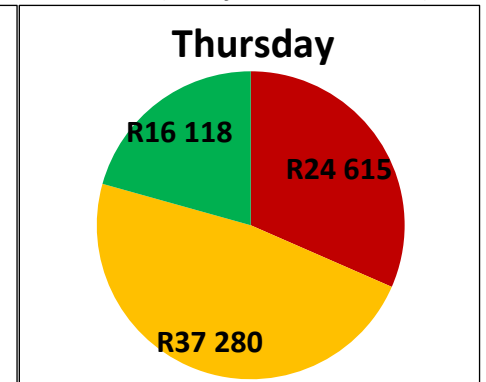
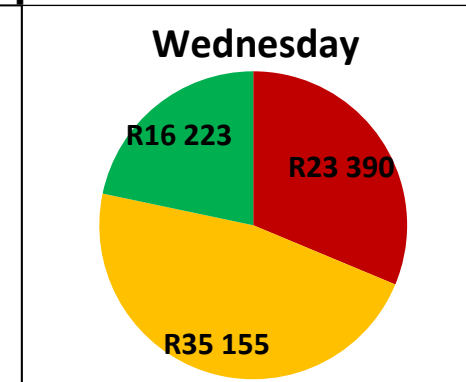
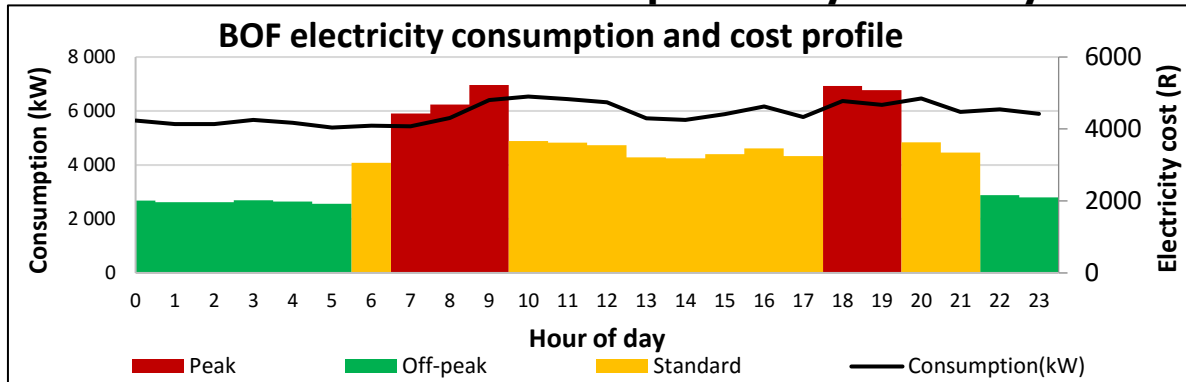
APPENDIX J: LADLE FURNACE LOAD SHIFTING MONITORING

J.1 DAILY STEELMAKING SCHEDULER REPORT

Appendix J.1 presents an example of a daily steelmaking scheduler report distributed as part of the ladle furnace load shifting monitoring discussed in Section 5.2.5. This is presented on the next page.

Scheduler report: Daily electricity consumption for 16 November 2017

(0% of data estimated)

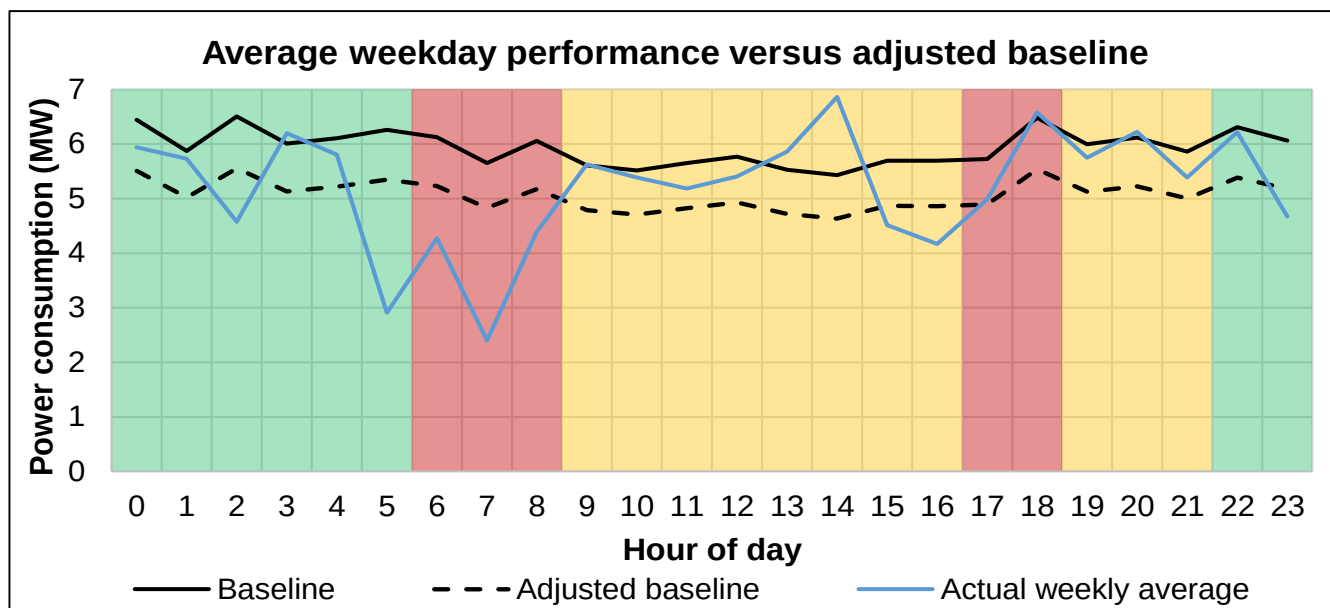


J.2 WEEKLY BASELINE SCALING FEEDBACK REPORT

Appendix J.2 presents an example of the weekly baseline scaling feedback report distributed as part of the ladle furnace load shifting monitoring discussed in Section 5.2.5. This is presented on the next page.

Steel plant: Ladle furnace load shift performance for 10 Jul '17 to 16 Jul '17

Cost benefit for 10 Jul '17 to 16 Jul '17: **R69 119**



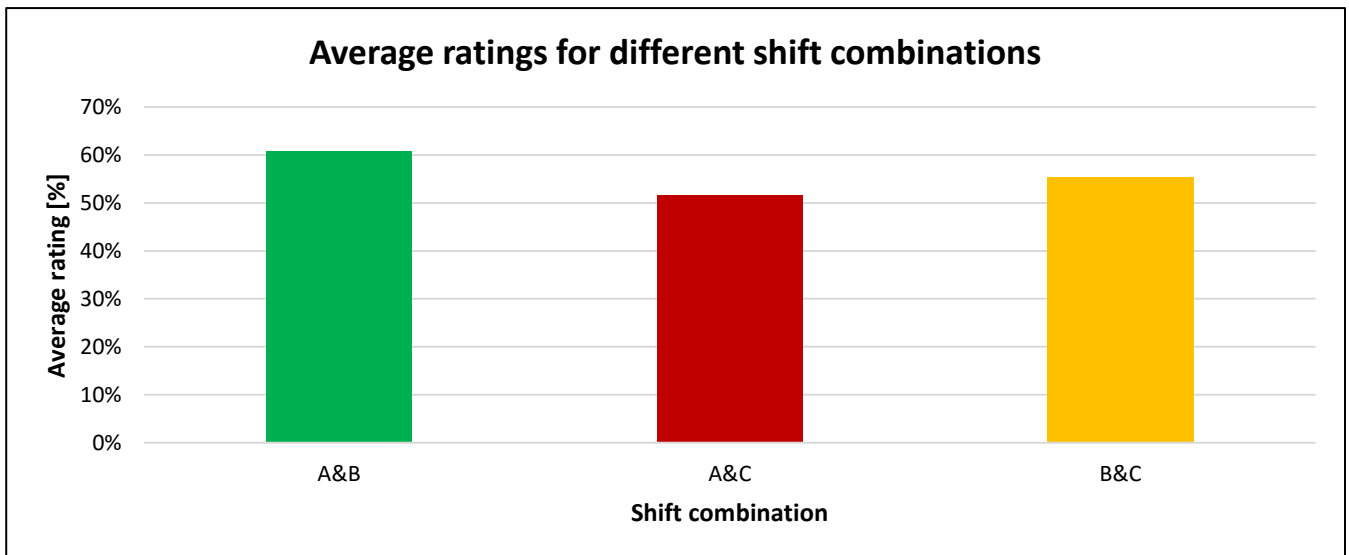
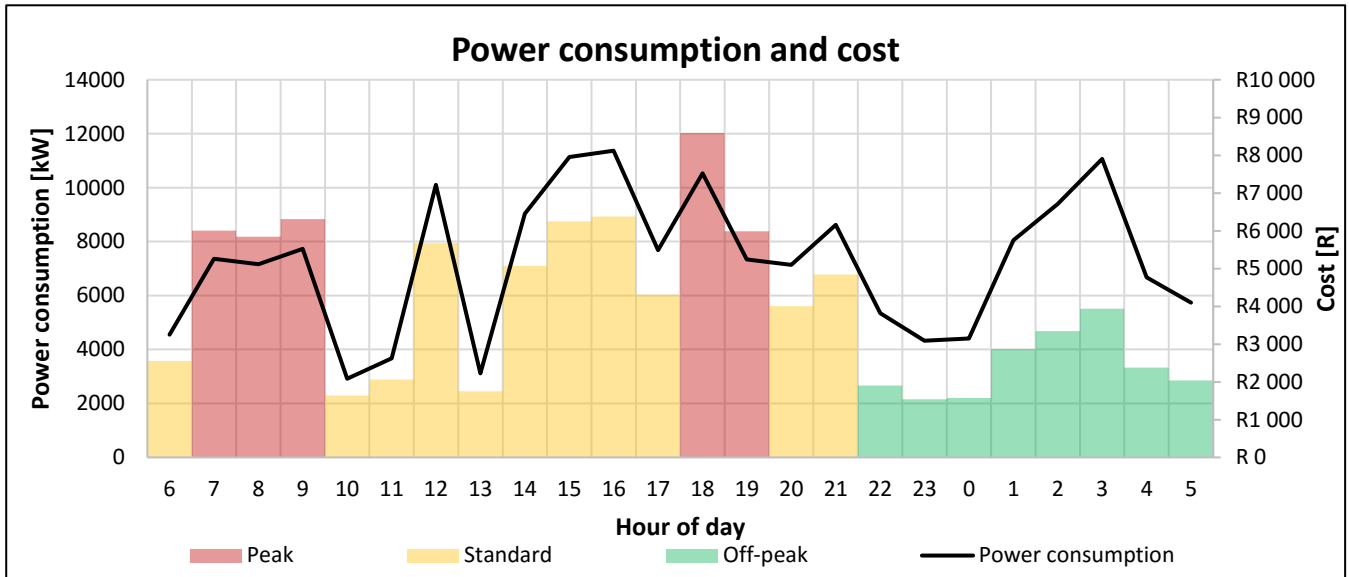
Week-to-date performance				
Date	Day of week	Adjusted BL cost [R]	Performance cost [R]	Cost benefit [R]
2017/07/10	Monday	R122 223	R121 052	R1 171
2017/07/11	Tuesday	R122 223	R141 103	R0
2017/07/12	Wednesday	R122 223	R105 946	R16 277
2017/07/13	Thursday	R122 223	R90 290	R31 933
2017/07/14	Friday	R122 223	R106 623	R15 600
2017/07/15	Saturday	R69 034	R65 479	R3 555
2017/07/16	Sunday	R54 569	R53 985	R584

J.3 LADLE FURNACE LOAD SHIFTING SHIFT RATING REPORT

Appendix J.3 presents an example of the shift rating report distributed as part of the ladle furnace load shifting monitoring discussed in Section 5.2.5. This is presented on the next page.

Steel plant: Ladle furnace load shift rating report

Rating for 06:00 on 22 Sep '17 to 06:00 on 23 Sep '17: **39%** [Shift combo: B&C]

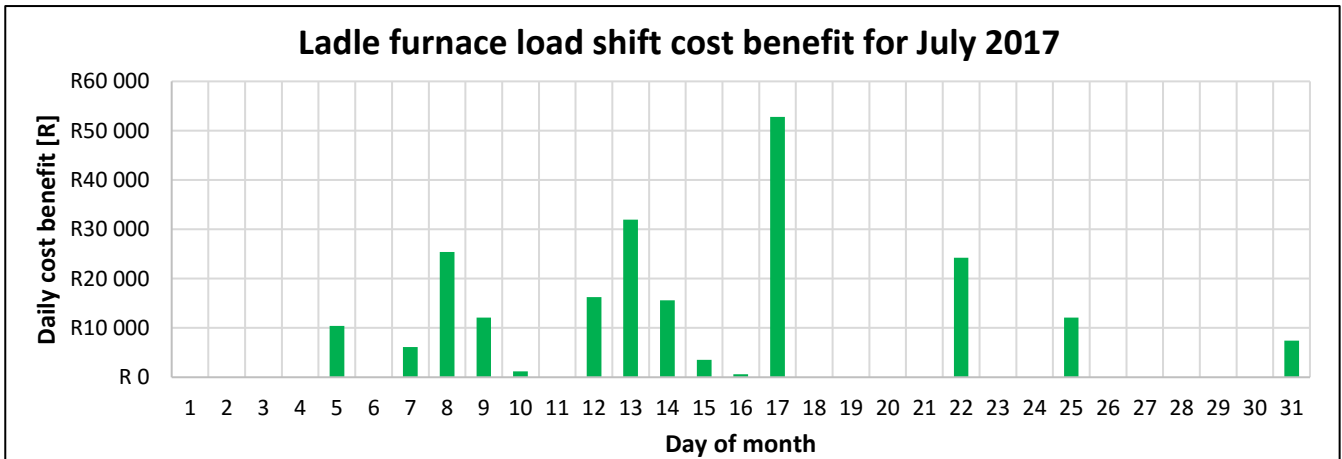


J.4 MONTHLY BENEFIT SUMMARY REPORT

Appendix J.4 presents an example of the monthly benefit summary report distributed as part of the ladle furnace load shifting monitoring discussed in Section 5.2.5. This is presented on the next page.

Steel plant: Ladle furnace load shift performance report for Jul '17

Cost benefit for Jul '17: **R219 728**



Month-to-date performance	
Date	Cost benefit [R]
2017/07/01	R0
2017/07/02	R0
2017/07/03	R0
2017/07/04	R0
2017/07/05	R10 434
2017/07/06	R0
2017/07/07	R6 151
2017/07/08	R25 404
2017/07/09	R12 097
2017/07/10	R1 171
2017/07/11	R0
2017/07/12	R16 277
2017/07/13	R31 933
2017/07/14	R15 600
2017/07/15	R3 555
2017/07/16	R584
2017/07/17	R52 767
2017/07/18	R0
2017/07/19	R0
2017/07/20	R0
2017/07/21	R0
2017/07/22	R24 211
2017/07/23	R0
2017/07/24	R0
2017/07/25	R12 109
2017/07/26	R0
2017/07/27	R0
2017/07/28	R0
2017/07/29	R0
2017/07/30	R0
2017/07/31	R7 436

APPENDIX K: HOT CHARGING MONITORING

K.1 HOT CHARGING BASELINE REGRESSION MODELS

Overview

A summary of the regression models used for the baseline of the hot charging of the primary rolling mill furnace initiative was presented in Figure 41 (Section 5.2.5). A detailed discussion of all the regression models are provided in this appendix.

Furnace 1 [COG]

The regression model was compiled from data for which more than 50% of the gas energy was obtained from *coke oven gas (COG)*, and only *Furnace 1* was used. The data points and relevant regression model are presented in Figure 82.

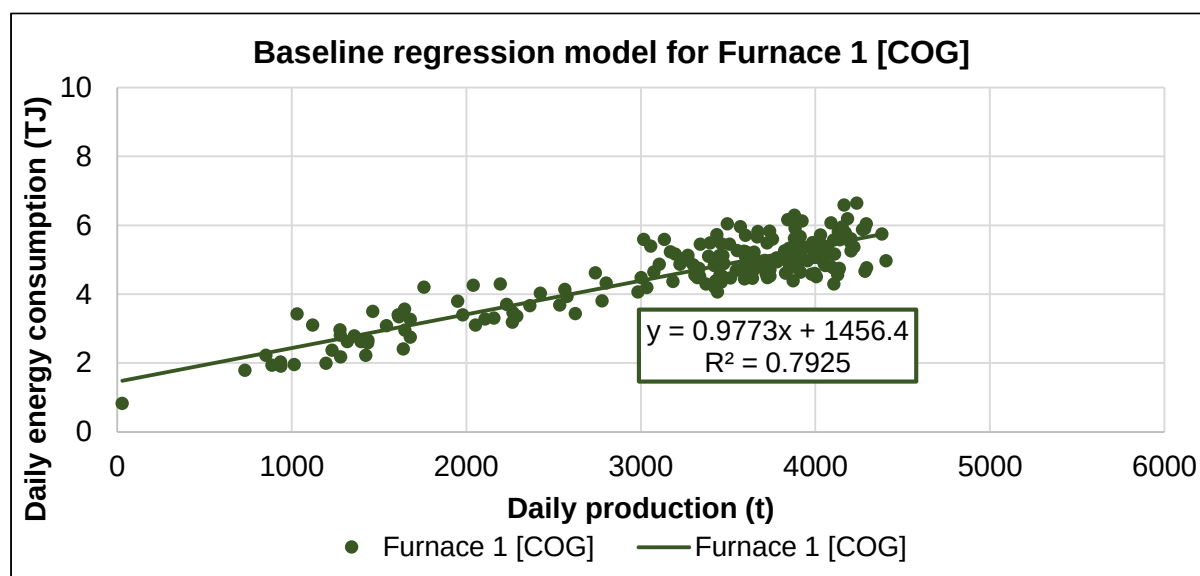


Figure 82: Furnace 1 [COG] regression model

Furnace 2 [COG]

The second regression model was compiled from data for which more than 50% of the gas energy was obtained from COG, and only *Furnace 2* was used. The data points and relevant regression model are presented in Figure 83.

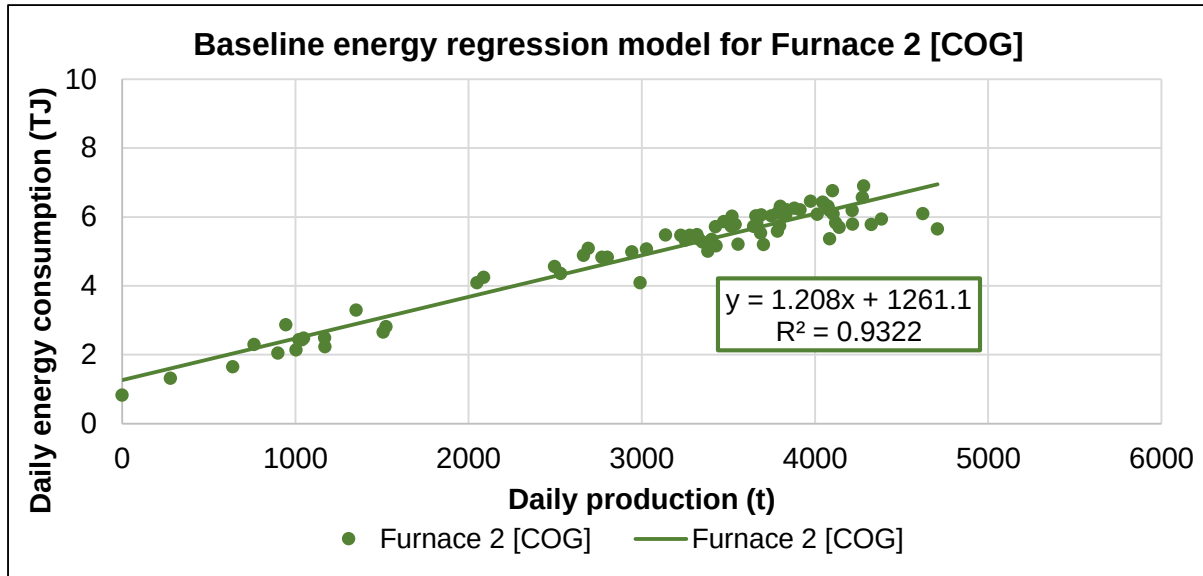


Figure 83: Furnace 2 [COG] regression model

2 Furnaces [COG]

The third regression model was compiled from data for which more than 50% of the gas energy was obtained from COG, and both *Furnace 1* and *Furnace 2* were used. The data points and relevant regression model are presented in Figure 84.

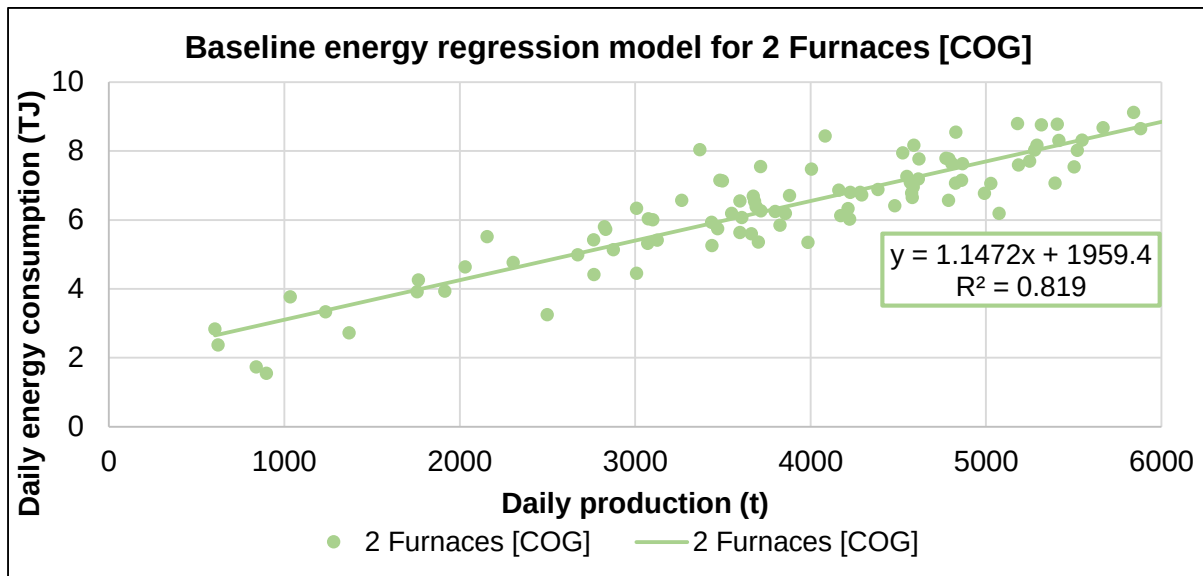


Figure 84: 2 Furnace [COG] regression model

Furnace 1 [NG]

The fourth regression model was compiled from data for which more than 50% of the gas energy was obtained from *natural gas*, and only *Furnace 1* was used. The data points and relevant regression model are presented in Figure 85.

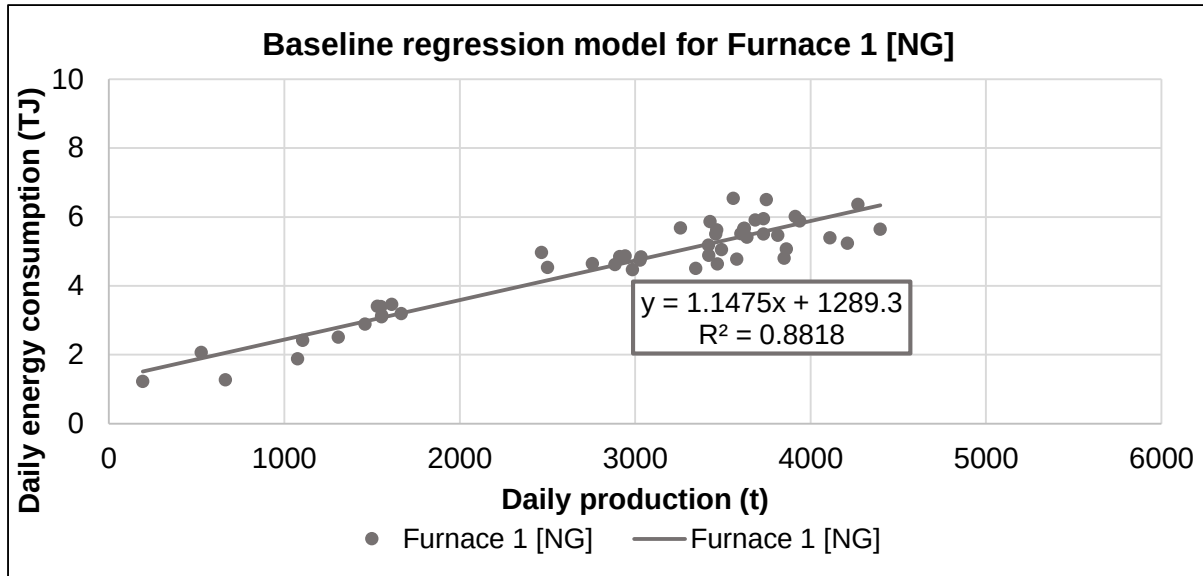


Figure 85: Furnace 1 [NG] regression model

Furnace 2 [NG]

The fifth regression model was compiled from data for which more than 50% of the gas energy was obtained from *natural gas*, and only *Furnace 2* was used. The data points and relevant regression model are presented in Figure 86.

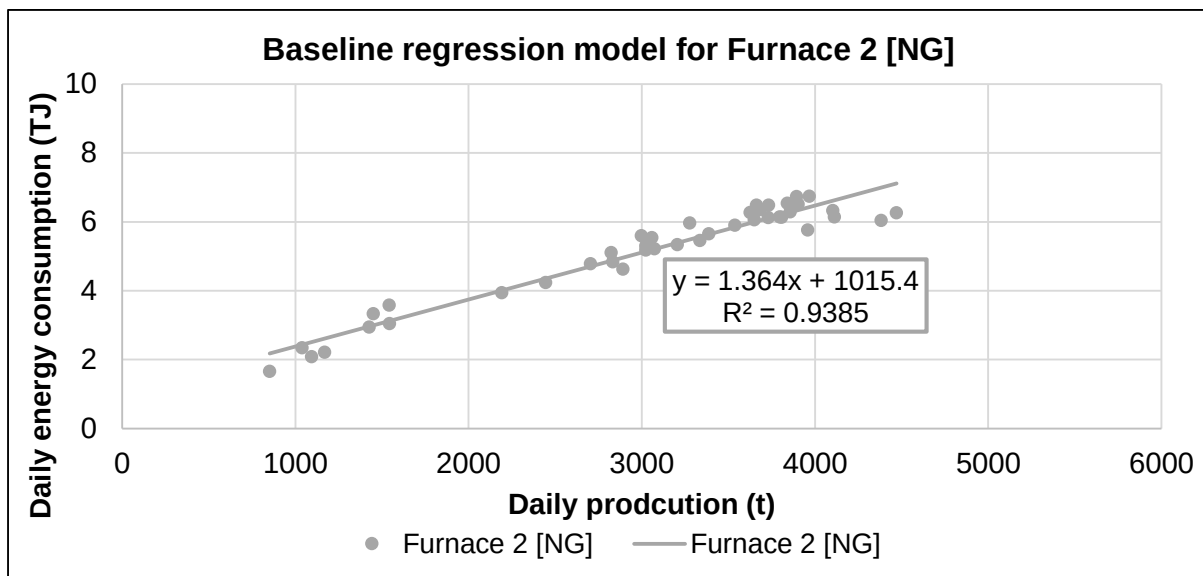


Figure 86: Furnace 2 [NG] regression model

2 Furnaces [NG]

The last regression model was compiled from data for which more than 50% of the gas energy was obtained from *natural gas*, and both *Furnace 1* and *Furnace 2* were used. The data points and relevant regression model are presented in Figure 87.

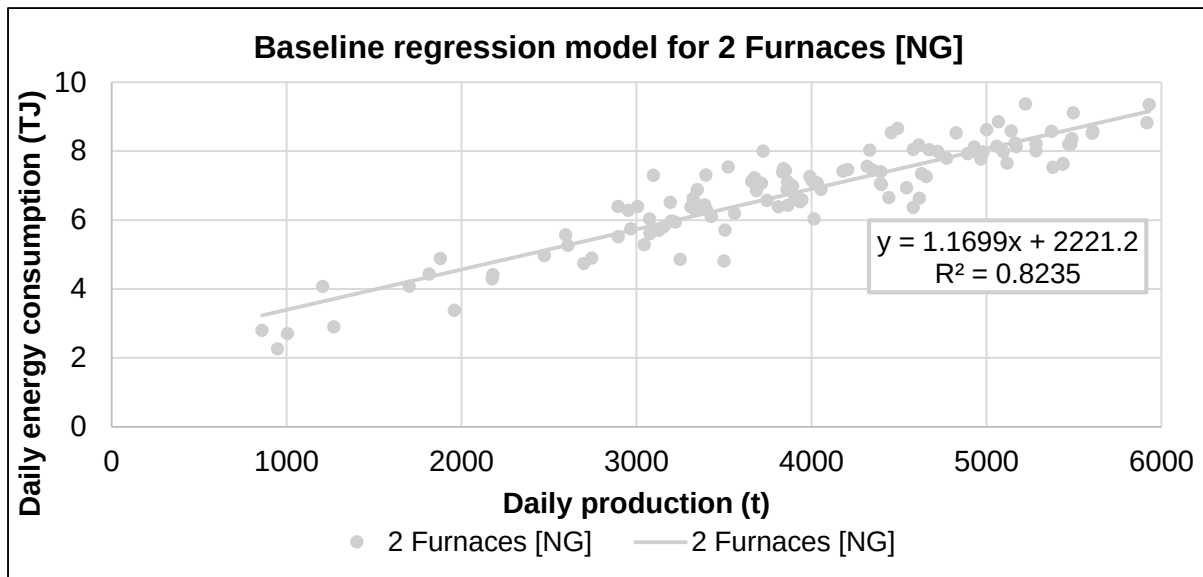


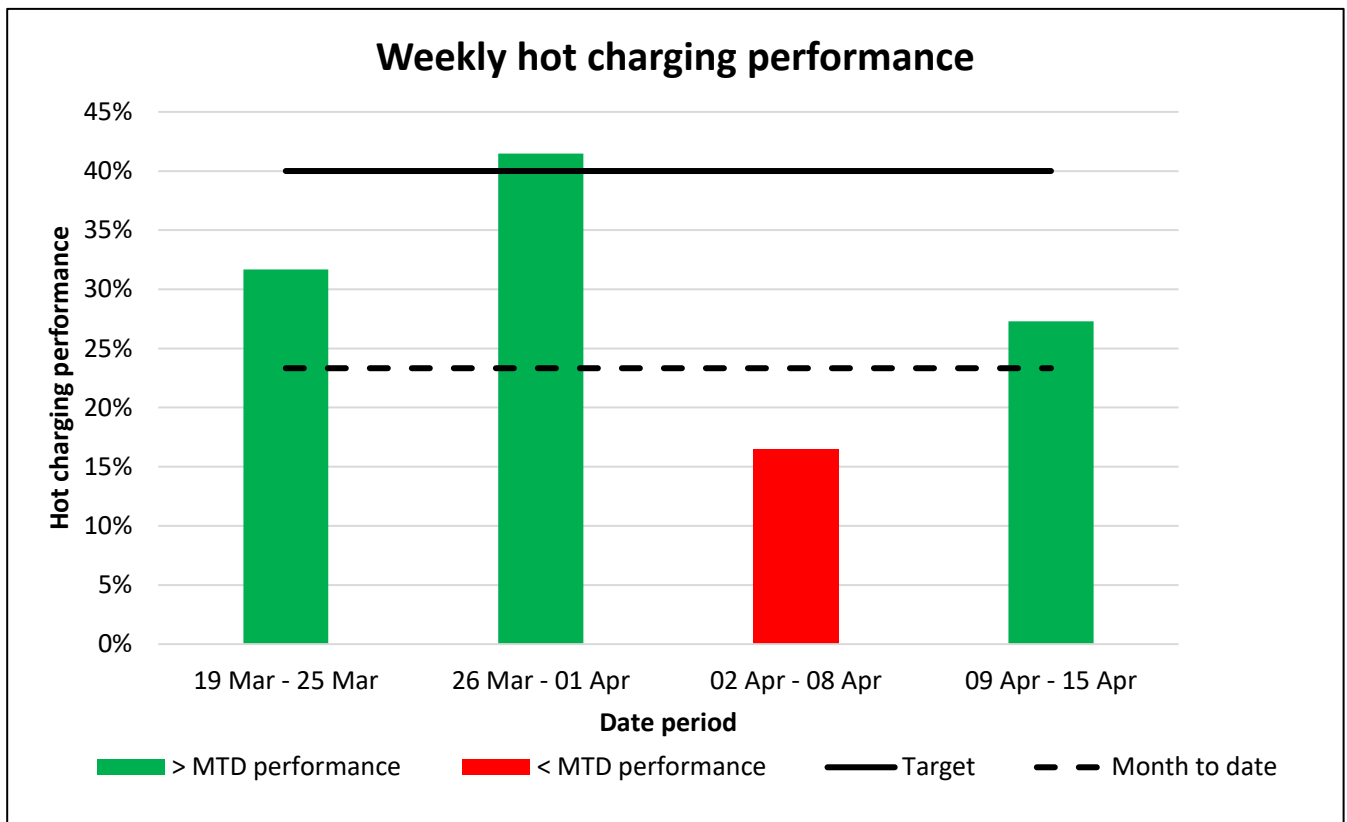
Figure 87: 2 Furnace [NG] regression model

K.2 DAILY FEEDBACK TO PLANNERS

Appendix K.2 presents an example of the daily feedback report distributed as part of the hot charging monitoring discussed in Section 5.2.5. This is presented on the next page.

Weekly hot charging performance feedback

Hot charging performance for 09 Apr - 15 Apr:	27.3%
Change from previous week:	Increased by 10.8%
Month-to-date performance for Apr '18:	23.3%



K.3 HOT CHARGING SHIFT RATING REPORT

Appendix K.3 presents an example of the shift rating report distributed as part of the hot charging monitoring discussed in Section 5.2.5. This is presented on the next page.

Hot charging shift rating report for 5 April 2018

Hot charging for 5 April 2018

0%

[Mill shift combo: B&C]

[Planner shift combo: B&D]

Missed opportunity (<40% hot charging): **R37 000**

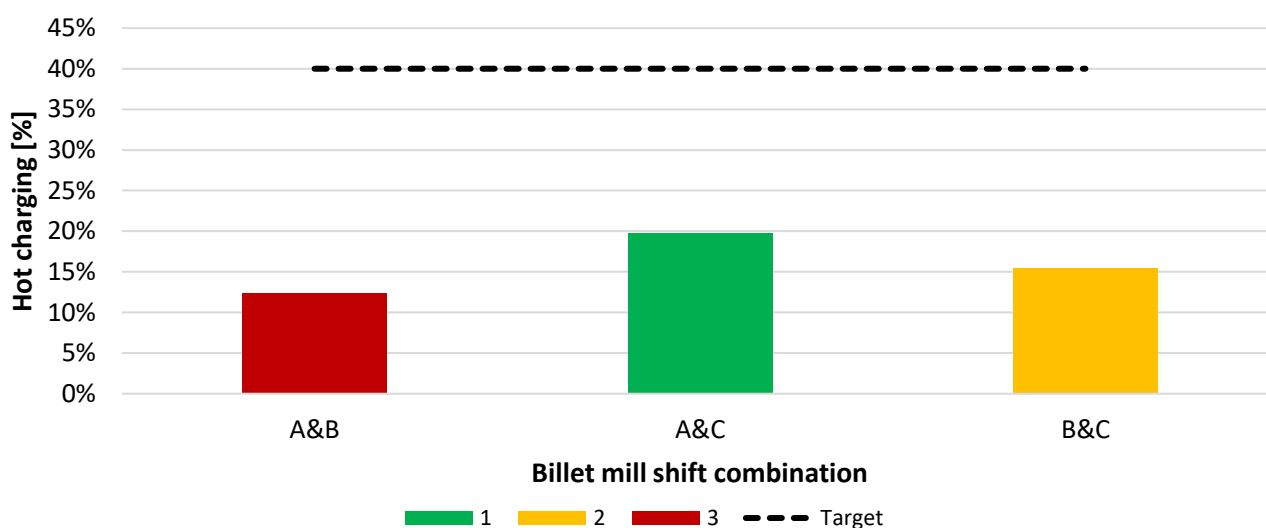
Achieved cost saving:

R0

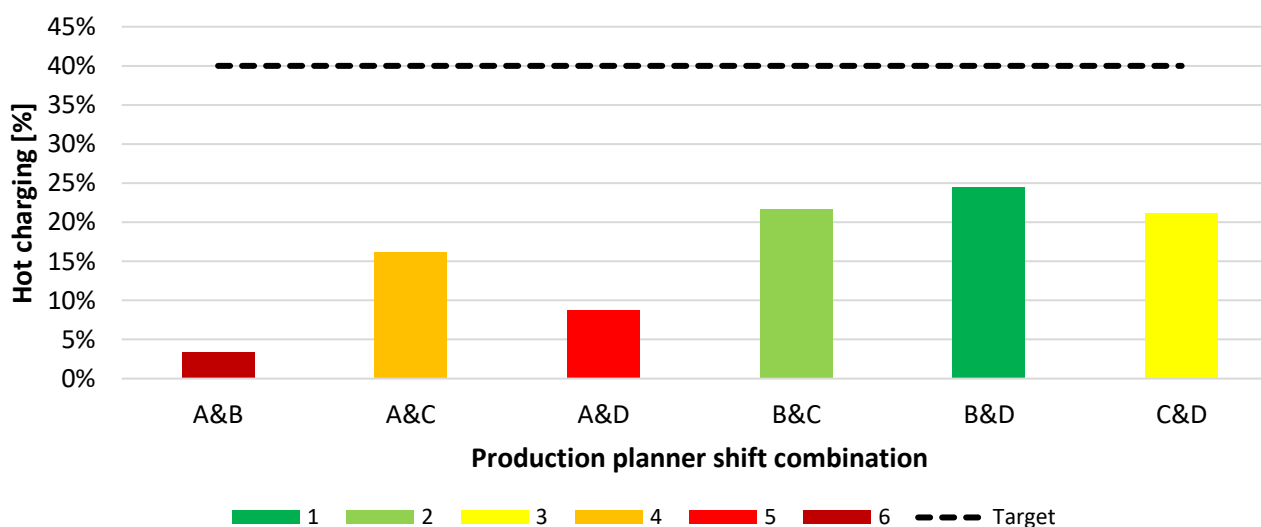
Month-to-date average hot charging:

23%

Percentage hot charging for primary rolling mill shifts



Percentage hot charging for production planning shifts



K.4 MONTHLY BENEFIT SUMMARY REPORT

Appendix K.4 presents an example of the monthly benefit summary report distributed as part of the hot charging monitoring discussed in Section 5.2.5. This is presented on the next page.

Performance assessment report
Primary rolling mill furnace hot charging

March 2018

1. Performance assessment overview

Improved hot charging

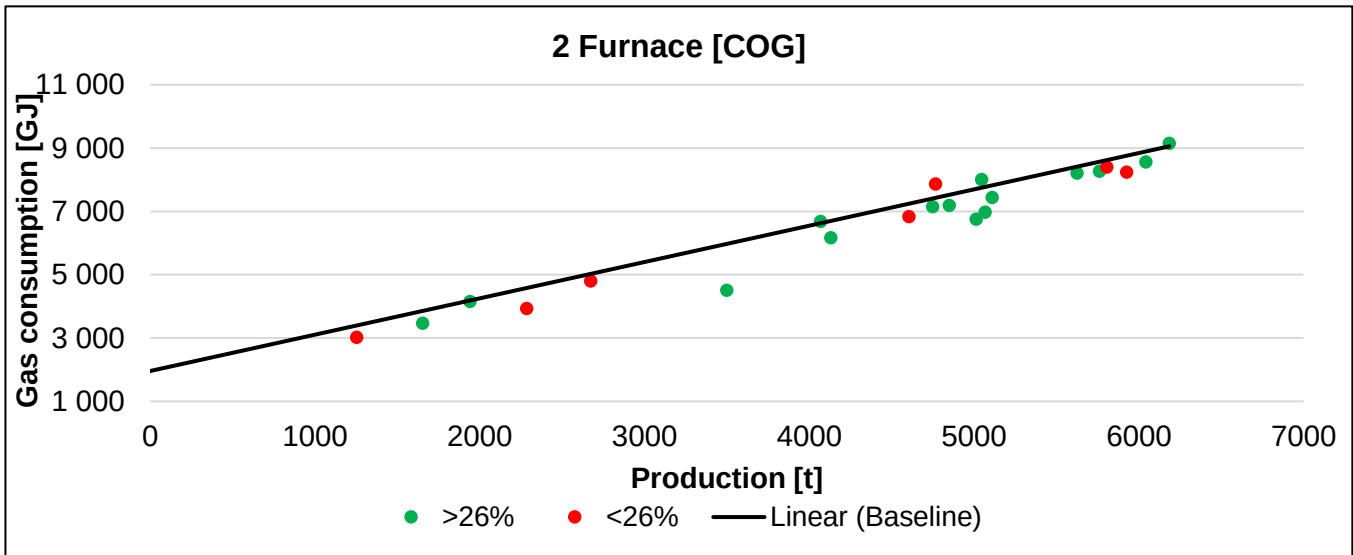
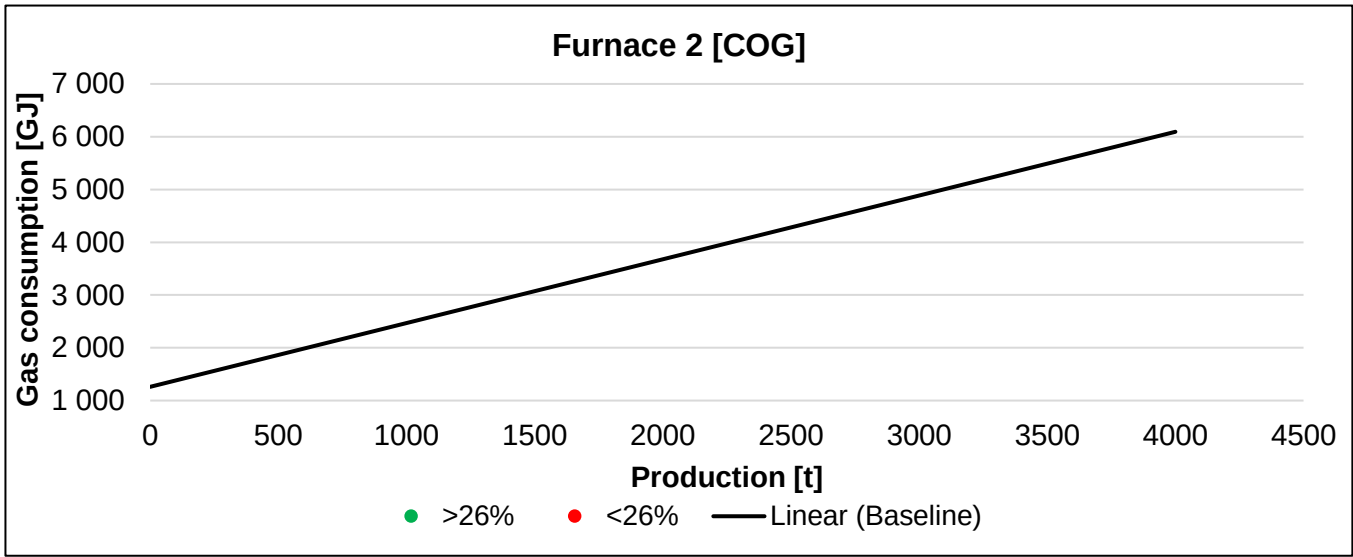
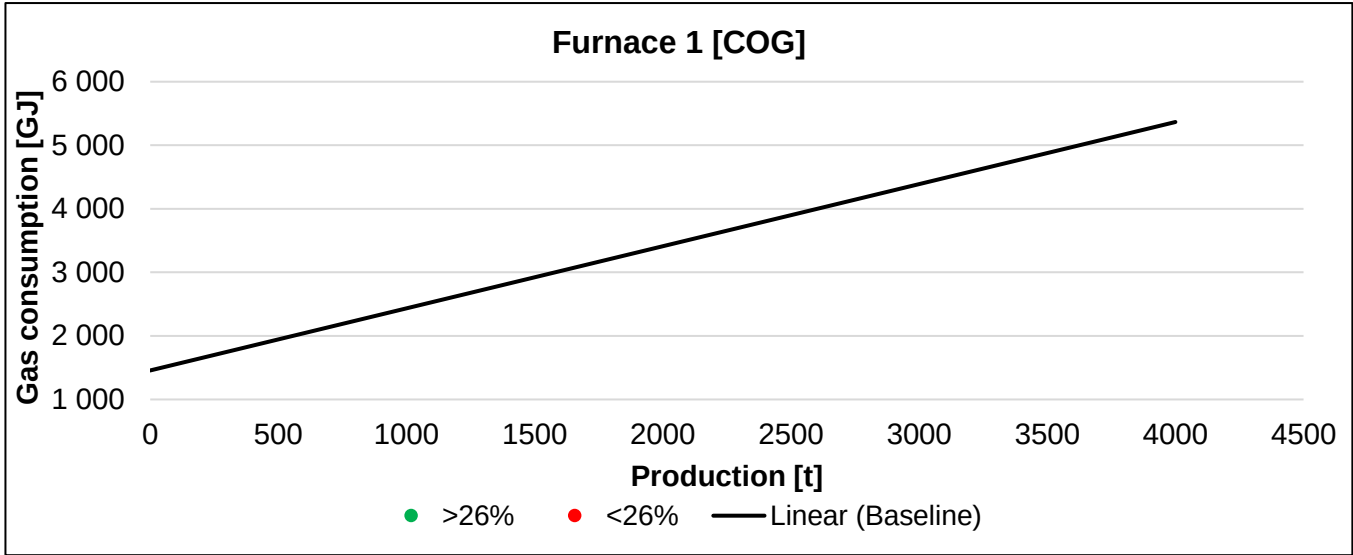
Actual hot charge: **32.6%**  Required hot charge: **26.0%**

Summary after removal of condonable days	
Total monthly production [t]	112 627
Total hot charge [t]	36 700
% hot charge for March 2018	32.6%
Effect on energy consumption [GJ]	7 744
Effect on cost [ZAR]	R480 105

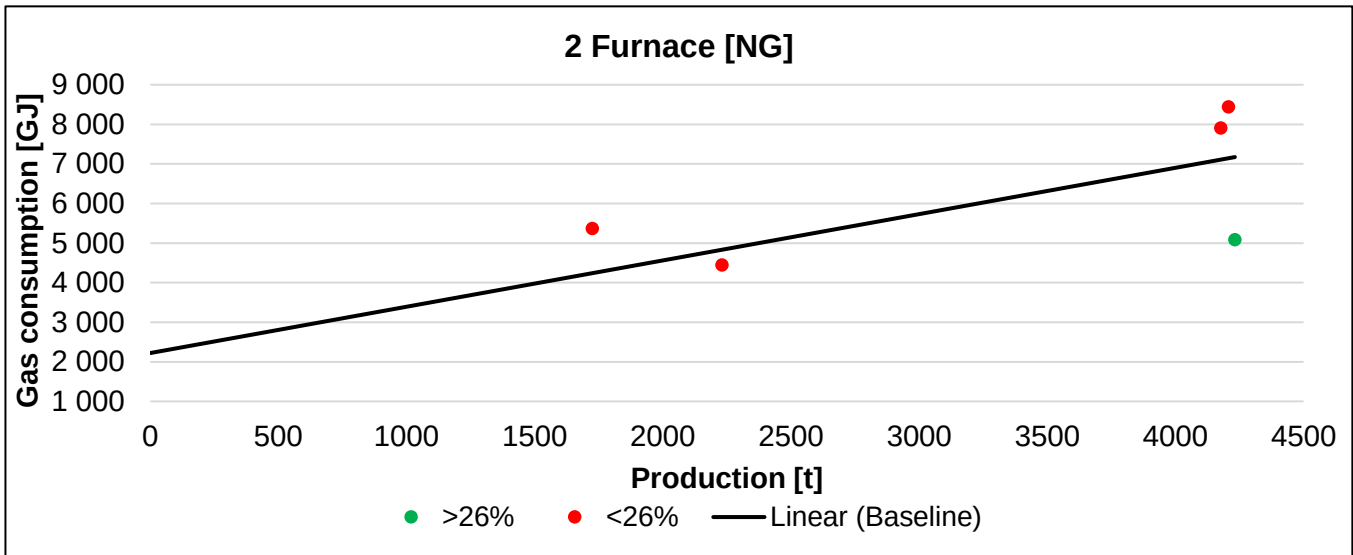
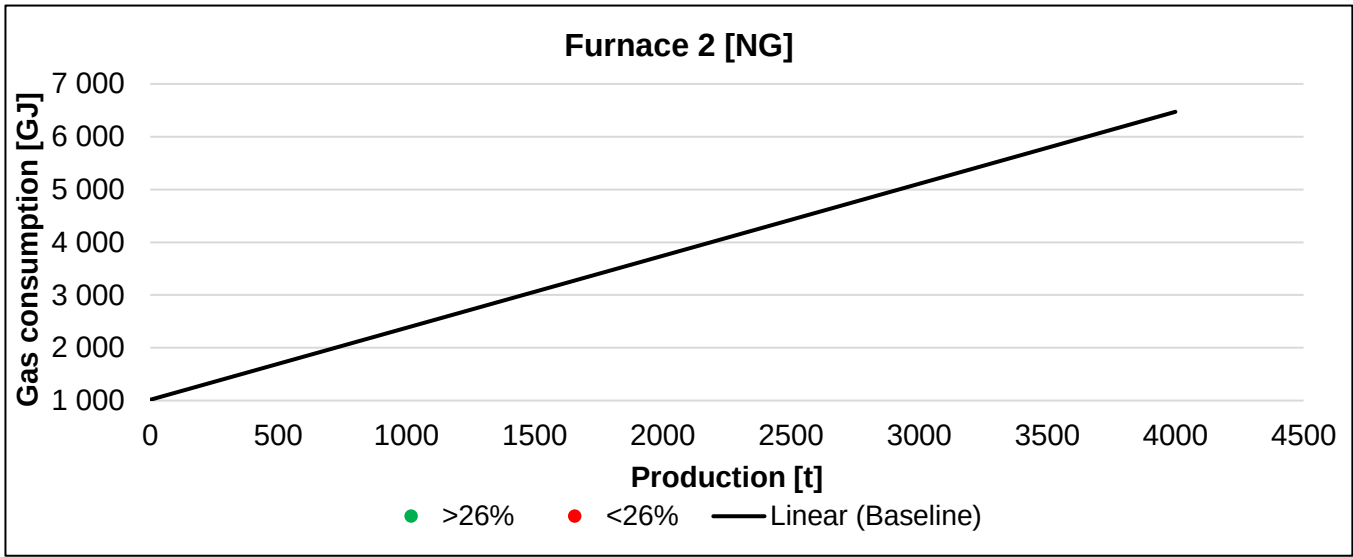
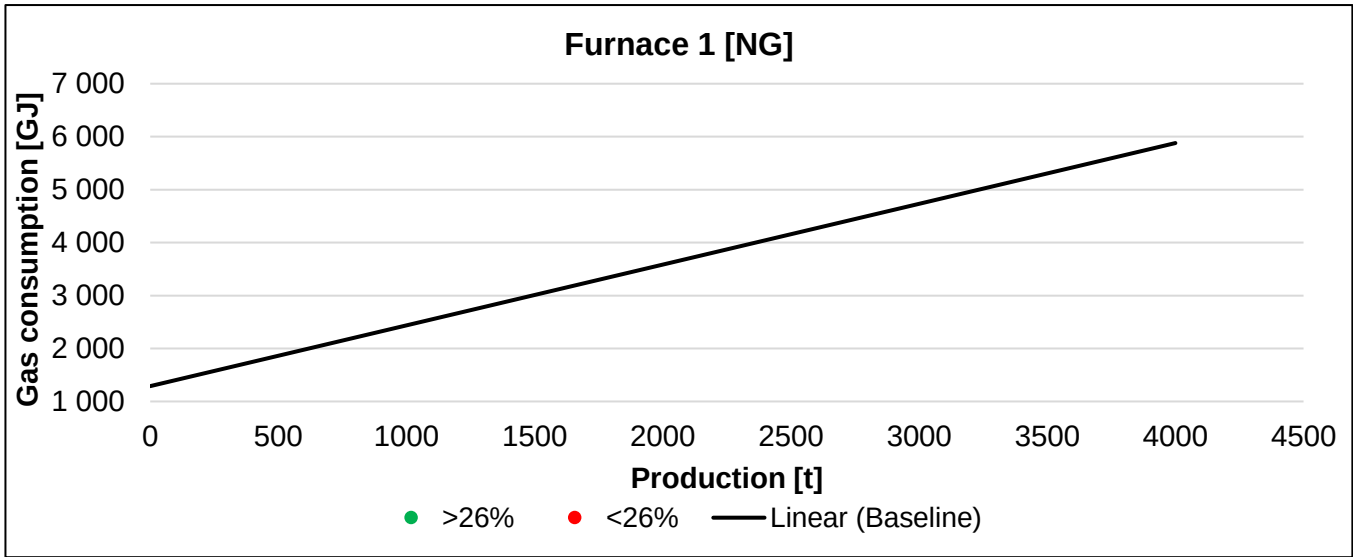
2. Daily performance overview

Date	Condone	Baseline model	Prod [t]	Direct [t]	Direct [%]	Gas [GJ]	Expected gas [GJ]	Gas effect [GJ]	Cost effect [ZAR]
01 Mar	No	2 Furnace [COG]	2 673	475	17.8%	4 799	5 026	n/a	R0
02 Mar	No	2 Furnace [COG]	5 762	2 290	39.7%	8 272	8 570	298	R18 488
03 Mar	No	2 Furnace [COG]	5 806	-	0.0%	8 402	8 620	n/a	R0
04 Mar	No	2 Furnace [COG]	5 068	2 222	43.8%	6 976	7 774	797	R49 427
05 Mar	No	2 Furnace [COG]	5 626	1 665	29.6%	8 204	8 414	210	R12 991
06 Mar	No	2 Furnace [COG]	4 131	2 671	64.7%	6 165	6 699	533	R33 059
07 Mar	No	2 Furnace [COG]	1 252	303	24.2%	3 026	3 396	n/a	R0
08 Mar	Yes	Condonable	1 664	-	0.0%	3 443	n/a	n/a	R0
09 Mar	Yes	Condonable	2 071	-	0.0%	3 755	n/a	n/a	R0
10 Mar	Yes	Condonable	3 236	-	0.0%	4 889	n/a	n/a	R0
11 Mar	Yes	Condonable	744	-	0.0%	2 839	n/a	n/a	R0
12 Mar	No	2 Furnace [NG]	4 177	-	0.0%	7 908	7 108	n/a	R0
13 Mar	No	2 Furnace [COG]	6 043	2 122	35.1%	8 565	8 892	327	R20 283
14 Mar	No	2 Furnace [COG]	5 926	1 428	24.1%	8 239	8 758	n/a	R0
15 Mar	No	2 Furnace [COG]	2 284	276	12.1%	3 936	4 580	n/a	R0
16 Mar	No	2 Furnace [COG]	5 014	3 483	69.5%	6 751	7 712	960	R59 545
17 Mar	No	2 Furnace [COG]	4 849	1 262	26.0%	7 190	7 522	n/a	R0
18 Mar	No	2 Furnace [COG]	4 604	-	0.0%	6 832	7 241	n/a	R0
19 Mar	No	2 Furnace [COG]	5 110	1 970	38.6%	7 437	7 822	384	R23 838
20 Mar	No	2 Furnace [COG]	4 068	1 110	27.3%	6 682	6 626	n/a	R0
21 Mar	No	2 Furnace [COG]	6 185	3 395	54.9%	9 154	9 055	n/a	R0
22 Mar	No	2 Furnace [COG]	1 653	793	48.0%	3 472	3 856	384	R23 811
23 Mar	No	2 Furnace [NG]	2 231	-	0.0%	4 449	4 831	n/a	R0
24 Mar	No	2 Furnace [COG]	1 940	648	33.4%	4 154	4 185	32	R1 954
25 Mar	No	2 Furnace [COG]	4 766	308	6.5%	7 869	7 427	n/a	R0
26 Mar	No	2 Furnace [COG]	4 749	2 291	48.2%	7 145	7 408	262	R16 269
27 Mar	No	2 Furnace [NG]	4 207	918	21.8%	8 440	7 143	n/a	R0
28 Mar	No	2 Furnace [NG]	1 725	294	17.0%	5 369	4 239	n/a	R0
29 Mar	No	2 Furnace [COG]	5 046	3 327	65.9%	8 002	7 748	n/a	R0
30 Mar	No	2 Furnace [COG]	3 500	1 578	45.1%	4 509	5 974	1 465	R90 812
31 Mar	No	2 Furnace [NG]	4 232	1 871	44.2%	5 082	7 172	2 091	R129 628

3. COG baseline comparisons



4. Natural gas baseline comparisons



Page intentionally left blank