Evaluating the price of different grades of chrome ore in South Africa

M Stoffberg

orcid.org 0000-0002-7507-7315

Mini-dissertation submitted in partial fulfilment of the requirements for the degree *Master of Business Administration* at the North-West University

Supervisor: Mr M Botha

Graduation May 2018

Student number: 21628025

ABSTRACT

The mining industry, being one of the largest industries in South Africa, is under review by investors due to the suggestions from the Department of Mineral Resources for revising the mining charter. There are growing concerns in the mining industry, should the revised mining charter be implemented. Although South Africa is a country rich in natural resources, these resources are imperishable and should be utilised as efficiently as possible. This study focuses on determining the equilibrium point between different concentrate grades in chrome ore. This is obtained using sales which varies with different grade of the input and waste material, with a specific focus on a gravitation wash plant.

A literature review was performed on the biggest chrome importing country (China), as well as the biggest exporting country (South-Africa). The focus was then placed on chrome itself and its products, namely steel and stainless steel. The empirical study focused on using the formulas addressed in the literature study to create a tool by combining them, which will indicate the equilibrium point of the selling price. This was applied to different grades and historical prices to illustrate the turning point in operations for different chrome concentrates. It was evident from the empirical study that the lower the selling price, the more beneficial it is to produce a higher percentage concentrate. Vice versa with the higher the selling price for concentrate products, the better is, the lower percentage concentrate, even with higher grade feed.

It is recommended that managers should use the model when a variable change, either in the plant or the sales price. The model will provide the answer if a change is needed in the product produced by the plant. Recommendation for future study is the effect the model have on related markets and the effect of Chrome VI on the model.

Keywords: chrome, mining, grade, price, China, South Africa

ACKNOWLEDGEMENTS

Without a proper support system, I don't know where I would be, and therefore I would like to thank the following:

- Heavenly Father, for blessing me through this journey and life.
- My family: Dad Stoffies, Mom Christa, Hestia and Kleins, for I am surely the most blessed person alive. Thank-you for support, motivation, guidance and prayers.
- My friends, for their patience with me
- Mr. M. Botha of the North-West University for the guidance and direction and abundance of patience as well as Prof. A. Smit for the additional support.
- Antoinette Bisschoff, for the "after-hours" language editing.
- And all the behind the scene support from clients who became colleagues who are now my friends.

ABBREVIATIONS

BIC:	Bushveld Igneous Complex
CIF:	Cost, Insurance and Freight.
COSATU:	Congress of South African Trade Unions
CSR:	Corporate Social Responsibility
DMR:	Department of Mineral Resources
DMT:	Dry metric ton
IDSR:	Industrial Demand-Side Response
ROM:	Run of Mine
USD:	United States Dollar
WHIMS:	Wet High-Intensity Magnetic Separation
ZA:	South Africa

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: NATURE AND SCOPE OF THE STUDY

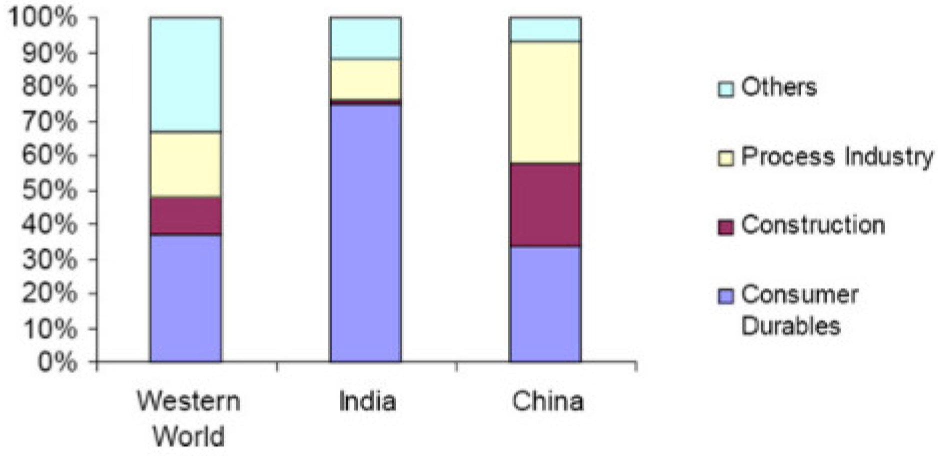
1.1 INTRODUCTION

Mineral resources are one of nature's gifts that is imperishable (Vela-Almeida *et al.*, 2015:189). The users must maximise its utility and not waste it (Richards, 2006:325). Proper resource development policies are important, especially in developing countries, as there is a constant tension between mineral exploitation and agricultural areas about the use of the land (Yuldashev & Sahin, 2016:266; Erdiaw-Kwasie & Alam, 2017:122).

Chrome ore is a mineral that is mined in the Bushveld Igneous Complex (BIC) which is located along the towns of Rustenburg, Brits, Witbank, Lydenburg and Steelpoort in South Africa (ZA) and around 90% of chrome ore is used in the metal industry (Murthy *et al.*, 2011:375; Xiaowei Pan, 2013:352). The chrome market is mainly driven by the world's demand for ferrochrome and stainless steel (Cramer *et al.*, 2004:517). The chrome mining sector is the world's largest producing sector, and China is the biggest importer while South Africa is the biggest exporter of chrome ore (Bhandary *et al.*, 2016:1097; ReportBuyer, 2017:1). For this reason, the study will focus on these two countries.

There are different methods available to extract chrome concentrate from Run of Mine (ROM) material, for instance, flotation or cyclone method (Das, 2015:336). This study will focus on a water gravity process, specifically a spiral-process for the extraction of chrome-ore, as a spiral uses the concept of a cyclone. Previous studies reveal the effectiveness of the recovery of minerals for this process (Das, 2015:336). The end-product of chrome ore is stainless steel which is a desirable metal because of its characteristics such as antirust (Baddoo, 2008:1199; Beukes *et al.*, 2017:874). This is one of the characteristics of stainless steel that differentiate it from steel. Figure 1 illustrates in which sectors of the industries in the Western world, India and China stainless steel was consumed that was produced from chrome ore. This illustrates how stainless steel is influenced differently globally due to alteration of consumption for each sector of the different countries. Prices for stainless steel are influenced by global conditions which include exchange rates, supply and demand of ROM, ferrochrome and stainless steel (ReportBuyer, 2017:1).

Figure 1: Stainless Steel Consumption by Sector Comparison according to BHP Billiton and OECD



Source: (Baddoo, 2008:1200)

According to most countries' laws and common practice with the monetary value of minerals (Uberman, 2014:501), management has a corporate social responsibility towards their stakeholders to deliver profits and continuity within ethical decision making (Hamann & Kapelus, 2004:85). When referring to sustainability for minerals and metals, one of the important factors mentioned is economic efficiency (Petrie, 2007:98). In this content, the concept of developing a model was created to consider more variables by not only looking at sales price but also mining-plant efficiency and combining these variables to determine the better outcome for the company.

Industrial Demand-Side Response (IDSR) was first defined in 1984 as load management, but over the years this concept was developed into IDSR. Initially, the concept focused on the demand response to changes in electricity prices but some studies referred to it when a company responds to changes in the market (Warren, 2014:942). This concept is used by amongst others a production plant that changes the amount they produce according to the electricity prices (Hadera *et al.*, 2015:117). This concept will be further explored in this study, but instead of reacting to changes in the cost of electricity, it will aim to create a model that react to the changes in the market value of products.

For the production of ferrochrome, which is used to make stainless steel, different compositions of chrome ore and chrome-concentrate are needed (Farjadi & Azari, 2004:104). The product of chrome ore and -concentrate, is expressed as a percentage chrome content per unit of dry metric ton. One of the parameters that will be set for the empirical study is that only two chrome content units will be used, namely 42% and 44% chrome concentrate. These are two types of unit concentrate exported by South Africa to China on a CIF basis (FerroAlloyNet, 2017).

Since 2008, global economies have experienced uncertainty with commodity prices related to the steel industry being very volatile (Firoz, 2014:2). The changes in market price of commodities influences mining decisions which impact the quality spread in input material (Cramer *et al.*, 2004:526). In a spiral plant, managers can react to these changes more efficiently provided they have the right tools. The accurate measurements in any metallurgical facility are the key to an efficient operation (Bascur & Linares, 2006:696) with the focus on the plant and not revenue management. Predictive price optimisation is a revenue management concept for product prices and sales quantities (Ito & Fujimaki, 2017:3). By combining efficient plant with price optimisation, a model can be created to support managers in decision making.

1.2 PROBLEM STATEMENT

Changes in legislation in South Africa and China is creating more emphasis on the Corporate Social Responsibility (CSR) of companies in the mining industry (Wang *et al.*, 2016:35-36). Every company has the CSR to utilise the imperishable resources as efficiently as possible and minimise losses (Uberman, 2014:498). With the economy struggling to recover from the recession of 2008, and still very restricted, it is important to make the decisions that are financially beneficial while maintaining a responsibility to all stakeholders (Blitz, 2017:26).

Chrome concentrate producers using spirals, or a gravity separation process, should know the variables in their plant, for instance, the percentage of chrome in feed material or waste, to optimise profits. This study will focus on managers' need to use this information to react to market prices offered by determining what product is financially more beneficial to produce. This study explores the different percentages of feed material and the effect changes in the spiral could have on the output material, namely product and waste material. In this study, reference to the waste material is made as "tailings".

Some research has been performed on the efficiency of a spiral for different mineral resources focusing on the variables that can be controlled. This study will focus on the economic advantages between different grades of chrome by answering the question: Is it better to produce a chrome concentrate of 42% rather than 44% at different sales prices and input grades of the material?

Based on the literature review the following scenarios will be investigated and tested in the case study:

Scenario 1: Same percentage chrome in the tailings for both products.

Scenario 2: 2% difference in the tailings. The higher product will have the higher percentage in the tailings.

Scenario 3: 5% difference in the tailings with the higher product causing, the higher percentage of the tailings.

For the above three scenarios, further variable scenarios of price difference where created based on historical price data. The following three best scenarios were identified:

- Price variable scenario 1: Price difference of $2.50, the minimum price difference.
- Price variable scenario 2: Price difference of $20.00, the most common price difference.
- Price variable scenario 3: Price difference of $40.00, the highest price difference.

These scenarios will be investigated with the following changes in assumptions: The above scenarios will be studied with the assumption of 15% in the tailings. This assumption will then be changed to 20% and applied to the above scenarios. It is important to illustrate both scenarios as it illustrates the difference in efficiency. The above scenarios will be investigated in chapter 3.

1.3 OBJECTIVES OF THE STUDY

1.3.1 Primary objective

The primary objective of this study is to develop a model that could assist in calculating the most viable point of production for different grades of chrome concentrate based on chrome grade in feed and tailings as well as current price. This point will be financially more beneficial to produce a chrome concentrate of 42% rather than a 44% depending on the sales price and input grade of the material. The equilibrium price, or for this study the turning point, is where the opportunity cost is the same for 44% than for 42%. Opportunity cost in this study refers to the possible income that could be generated based on the scenario. When the opportunity cost is less for a 44% than for a 42% a change in product is required creating the turning point for production. Then it is more beneficial to change from producing a 44% to a 42%. The opposite also applies.

1.3.2 Secondary objectives

To achieve the primary objective, the following secondary objectives were formulated:

1.3.2.1 In the literature study:

- Conceptualise from the literature the steel and stainless-steel industry;

- Conceptualise from the literature the Chinese and South African macro, as market indicators and end-users of chrome;
- The study will conceptualise from literature mining in South Africa, especially chrome ore;
- Exploring chrome ore and discuss the beneficiation process and the relevance to the Industrial Demand-Side Response (IDSR)-concept;
- Describing the mass recovery formula and the relevance to the model; and
- Describing the total sales formula and the relevance of pricing to the model.

1.3.2.2 In the empirical study:

- To create the model by combining different variable formulas;
- To test the model as a case study with different scenarios;
- The pricing of chrome will be investigated; and
- Determining the effectiveness and necessity of the model by using historical data and illustrating it with different examples.

1.5 RESEARCH DESIGN

The design of the research is a case study due to its ability to explore, describe and explain real-life environment (Zainal, 2017:4). The advantage of using a case study as a method for this research is because it will apply the model to the real-life environment to illustrate the contribution of the study. The turning point will be illustrated in the form of a case study based on the different scenarios that will be developed. To illustrate the model graphically, different scenarios using price difference and other variables will be applied to the model.

1.5.1 Literature review

The literature review will be done by using the latest and relevant journal articles, internet articles and websites, publications and discussion papers.

1.5.2 Empirical study

The research method utilised will be to develop a model and test it as a case study by applying different variables. The empirical study focusses on combining the following three formulas: mass recovery; sales and equilibrium formula. These formulas are widely used in practise and will be further explained in chapter 3. By combining these formulas a model will be created that illustrates the equilibrium point for chrome concentrate 42% and 44% products for the different scenarios identified. A range of sales prices and raw material chrome percentages will form the base of the scenarios while assumptions will be made on price difference and waste material.

1.6 CONTRIBUTION OF THE STUDY

A model will be developed out of three formulas. The development of the three formulas into a model can be utilised to determine the more financially beneficial chrome concentrate product to produce by including the market price and other variables such as input and waste material. This will provide managers in the chrome industry with a tool to be more efficient and profitable.

1.7 LAYOUT OF THE STUDY

Chapter 1: Nature and Scope of the study

The first chapter introduces the nature and the scope of the study where the objectives of the study are outlined, and the research question defined. The case study scenarios are introduced, and a final overview of the study is provided.

Chapter 2: Literature review

This chapter reviews the literature to obtain the knowledge regarding chrome and the relevant markets as well as beneficiation of chrome and the theory behind it. This is set to address the research objectives.

Chapter 3: Empirical study

This will be a case study observing different scenarios by applying the model development from combining the different formulas.

Chapter 4: Conclusions and recommendations

Based on the case study, conclusions will be made regarding the findings. Limitations will be explained, and recommendations will be discussed. Suggestions for future research will also be presented in this chapter.

1.8 SUMMARY

This chapter provided an introduction to the world of chrome and the necessity of it as a resource. It also introduced the connection to stainless steel and China and an introduction to the process of beneficiation. The problem statement was identified, and the research question was determined while an outlay of the study was provided. Chapter 2 will provide a more detailed discussion of the relevant areas and the connection to the study of chrome and the model that will be developed.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION:

This chapter will aim to understand the factors that influence the chrome market. This is aimed at supporting the case study by providing background on the model. The sectors that mandate the end-product will be discussed, followed up by a review of the countries determining the supply and demand of chrome. Further study is done on chrome ore and the beneficiation of the chrome ore, specifically in a spiral plant, before the formulas of the model is discussed.

2.2 BACKGROUND OF THE STEEL MARKET

Constantly we come into contact with steel products, such as cell phones and televisions, causing a growing global steel demand which is expected to grow until 2025 (Cho & Kong, 2017:38-39). Due to a decrease in demand in 2008, there was a change in the steel industry where innovation is expected throughout the whole process, to optimise profits (Blitz, 2017:26, 29). An opportunity for new entrants is created when innovation became available, and steel producers can't seize it due to the cost of capital (Lee & Ki, 2017:368).

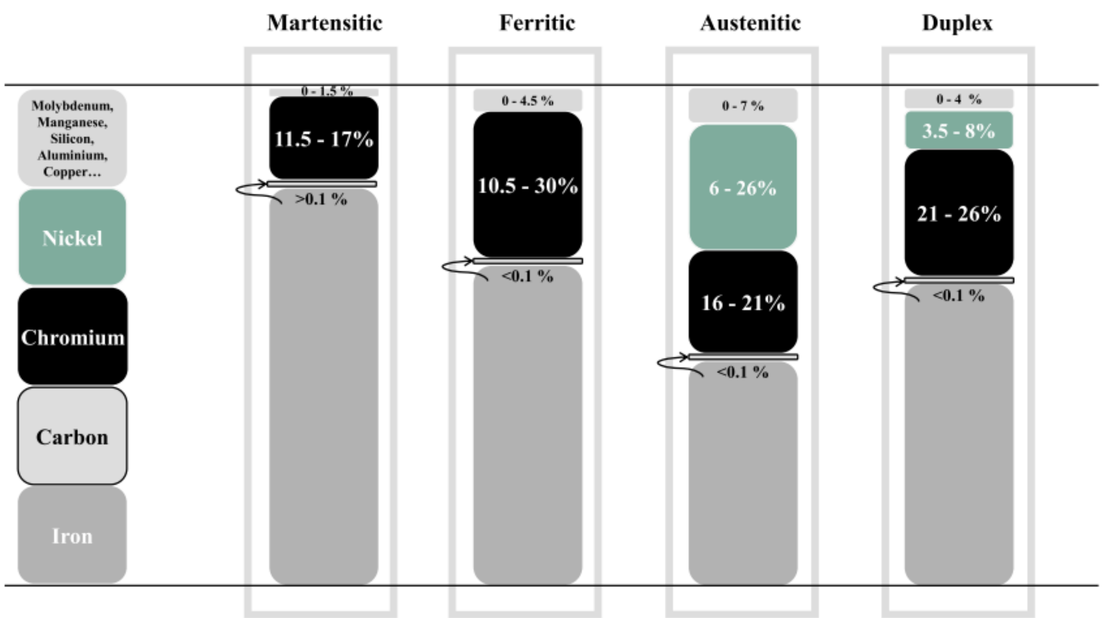
China is the biggest producer of steel, which is one of the biggest markets in industrial products (Arık & Mutlu, 2014:10). The production of steel is a large contributor to CO2 emissions, and China is the biggest producer has the highest impact on climate change due to steel production (Kuramochi, 2017:668). In an industry with such a high impact on the environment, not only with climate change but other factors as well, it is expected of steel producers to look at the sustainability of their operations and the effect it has on the environment (Long *et al.*, 2016:133).

China, the leaders in the steel industry realise the importance of finding other developing markets to ensure growth despite the cost of being socially responsible (Ottosson & Kindström, 2016:119). This is due to global overcapacity that is currently negatively affecting production in developed countries like the United States (US). This resulted in job losses because of an oversupply of labour (Popescu *et al.*, 2016:538). Other industries or markets that affect or are affected by steel demand is real estate-; transportation-; electrical and mechanical-; and the special equipment industry (Sun *et al.*, 2017:13). Steel spot prices, the prices that the market is willing to pay on the spot for the product at a certain place, reflects the production and trade of steel. This strengthened the relationship with other metals traded on the exchange or screen (Arık & Mutlu, 2014:10). A complement industry that is activated by steel production is the stainless steel market (Cyril *et al.*, 2017:1). A closer look at the stainless-steel market will be discussed next.

2.3 STAINLESS STEEL MARKET

Growth in the stainless steel market is between 5-6% per year despite occasional slumps in the economy (Cramer *et al.*, 2004:517; ISSF, 2017:4). This growth is important as it influences the demand for its inputs such as chrome, which is important within the context of this study. To create stainless steel ferronickel, ferrochrome and ferromolybdenum are melted together and this stainless steel is used for products like medical equipment (Jujur *et al.*, 2015:1185). The ferrochrome that is used with other material, by melting chrome ore, will produce stainless steel (Das, 2015:336). There are four families of stainless steel namely: martensitic, ferritic, austenitic and austenitic-ferritic dependant on their properties (Rossi, 2014:183). Figure 2 illustrates the four families and the combination of different mineral resources needed to produce each member. Possibilities are increasing in the construction market for different uses of stainless steel, which creates an increase in the demand for stainless steel (Baddoo, 2008:1199). This will also carry over to the demand for raw materials which is illustrated in figure 2 and includes chromium. In the next section the biggest importer of chrome, namely China, will be discussed.

Figure 2: Different family chemical compositions in stainless steel



Source: (Rossi, 2014:183)

2.4 KEY ROLE PLAYERS IN THE CHROME ORE MARKET

2.4.1 China macro market

China is a developing country with a high growth rate of around 10% with the steel industry being the biggest contributor to their economic growth (Sun *et al.*, 2017:13). China is a steel-intensive economy with production of steel related products increasing due to infrastructure development (Wübbeke & Heroth, 2014:1). Challenges steelmakers in China are being faced with are serious financial setbacks with rising cost of raw material and low steel prices (Wübbeke & Heroth, 2014:1).

The “One Belt, One Road” initiative was introduced by China to increase growth in their economy by developing into other countries. This initiative will be able to help with the current excessive capacities in China’s steel market and also provide opportunities for stronger ties between the US and China (Swaine, 2015:12; Grossman, 2017:5). The One Belt, One Road-initiative is the development of the Silk Road Economic Belt and Maritime Silk Road policies, which is the development of infrastructure by creating new roads (Swaine, 2015:46). The chinese government is also focussing on building a stronger circular economy to promote a healthier society, especially in the steel industry which has high pollutant emissions (Ma *et al.*, 2014:505). The current incremental expansion of the mining industry in Africa is driven by Chinese investment (Edwards *et al.*, 2014:302). In the next section, one of these African countries’ (South Africa) role in the industry will be looked at in more detail.

2.4.2 South Africa mining industry

South Africa is very rich in mineral resources with a mining industry that has vast value generation potential (Lane *et al.*, 2015:473). As the geographical source of chrome, South Africa has dominated the chrome market with the reserves estimated at exceeding 75% of the global resources (Cramer *et al.*, 2004:518). The South African economic growth is affected by the behaviour of the mining industry, as unrest in the industry has historically shown more than 0.5 % negative change in economic growth (Horne, 2017:4). Mining is an important part of the South African economy, and it will be for decades (Ting, 2016:61). Stakeholders in the SA mining industry includes shareholders, community members, employees, unions and the Department of Mineral Resources (DMR). Community members are affected by the decisions made in developing the resources either financially or environmentally and should, therefore, take a keen interest in stakeholders (Erdiaw-Kwasie & Alam, 2017:122).

The DMR is the department with authority to make sure the mining companies abide by the governments’ territorialisation and other rules and regulations (Ting, 2016:69). The DMR introduced an updated draft version of the Mining Charter 2017 without consulting the rest of the stakeholders who created concerns and upset in the industry (Baxter, 2017:33). Concerns included unrealistic financial markets, change in Black Economic Empowerment requirements and the effect these changes have on investor confidence in South Africa. Currently, the DMR is under a lot of scrutinies because of its decisions, and it costs the mining industry to lose out on the global increase in demand for commodities (Miller, 2017:VI). There are pending court cases against the DMR and companies are considering suing inspectors in their personal capacity. Stronger leadership is required to accomplish the same vision (Keil & Ndou, 2016:1291) without which the mining industry will not be successful.

2.5 CHROME MINING IN SOUTH AFRICA

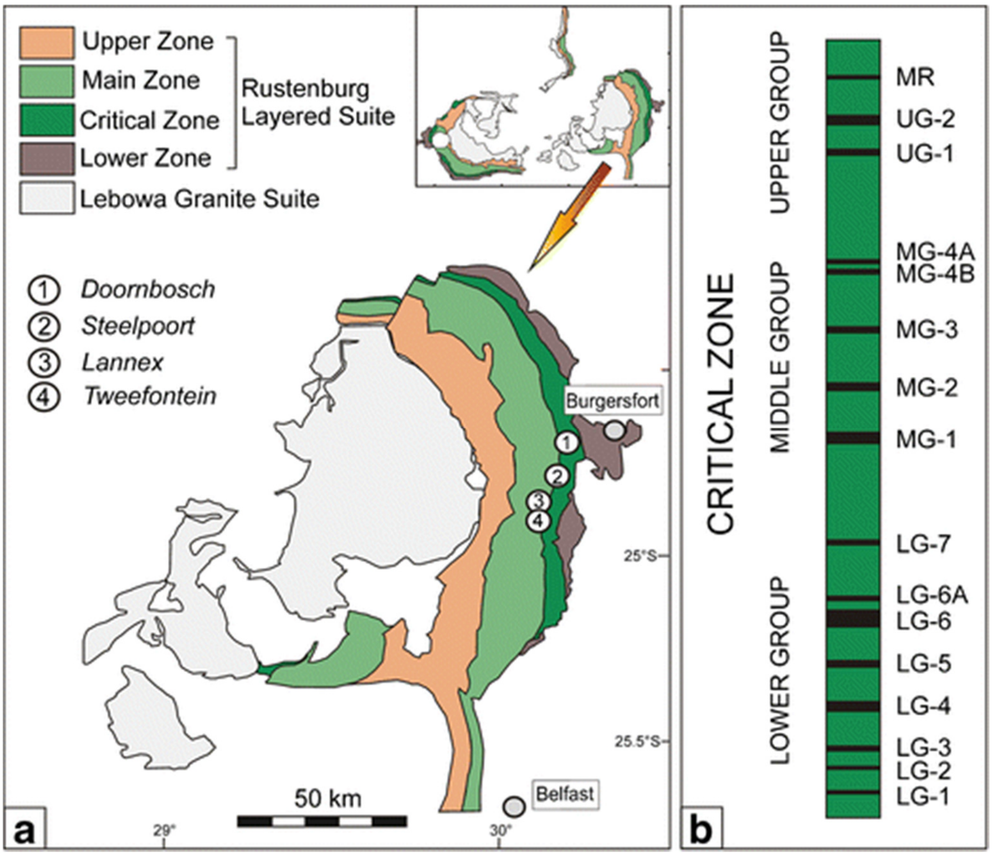
Territorialisation was introduced by the South African government to control the unrest in the mining industry in the form of boundaries. Landowners and/or miners want the rights to extract the minerals from the land, but when territorialisation was introduced in South Africa, all mineral resources belong to the government (Rasmussen & Lund, 2018:388). By being a big contributor to the Gross Domestic Product the mining industry has a big effect on the financial, environmental and social responsibility of developing countries (Basu *et al.*, 2015:158).

Instability in state institutions can cause mineral resources to be used inefficiently (Yuldashev & Sahin, 2016:266), and as South Africa's mineral resources now belong to the government, this is a big risk the country is facing. That is why the cry for nationalisation caused such negative sentiment towards investing in mining in South Africa (Lane *et al.*, 2015:472) as investors do not want to risk their money investing in instability and nationalisation.

Mining in South Africa started in 1871 when diamonds were discovered and grew into the funding instrument of the economy (Ting, 2016:60). There are two types of ways to mine, surface mining, which is referred to as open-pit mining and underground mining. Open-pit mining is mining of blocks for minerals resources while the underground focus on slope mining (MacNeil & Dimitrakopoulos, 2017:794). The cost of mining, whether it's opencast or underground is high, especially considering the capital required to develop underground. Both ways of mining are needed. The areas that are mined have a negative impact on tourism and the environment because it removes from nature and this is not what visitors want to see, especially if the company doesn't restore the mining area to what it was before they started. Since minerals and income generated from minerals have more value than heritage in the eyes of the government, the mining industry continues to negatively impact tourism (Leonard & Lebogang, 2017:4).

The chrome mining area in South Africa is located in the northern part of the country referred to as the Bushveld Igneous Complex. The surface exposure is over 240x350 km while the chrome is formed in layers underground (Li *et al.*, 2005:119). Figure 3 below is a map of the Bushveld complex which illustrates where the chrome can be found and the different layers that exist.

Figure 3: Geological map of Bushveld Complex



Source: (Oberthür *et al.*, 2016:73)

After the chrome was mined by either one of the two methods, the ROM (Run Of Mine) chrome ore has to be crushed or ground down before it can be further beneficiated (processed in a plant) or liberated (process of changing mineral to react better in the process) (Bhandary *et al.*, 2016:1097). Figure 4 is a picture of ROM chrome that has already been crushed from the Brits-area in the North-West Province; depending on the zone it was mined the colour can differ but should be grey. This is to illustrate the material that is needed for the beneficiation process.

Figure 4: Crushed chrome ROM before it is further processed into concentrate.

Source:(Stoffberg, 2017)

In the next section, chrome ore and concentrate is discussed.

2.6 CHROME ORE AND CONCENTRATE

Chrome consists of versatile and vital properties like resistance to corrosion, oxidation, wear, galling and enhancement of hardenability (Basu *et al.*, 2015:158). This is important in the production of stainless-steel, as that is how stainless-steel share all these properties with its end-user.

Over the years demand increased which lead to the mining of chrome ore from very high-grade deposits to the lower grade, as the availability of chrome is limited (Cramer *et al.*, 2004:518-519). Meaning the higher grade, which refers to a unit with higher percentage chrome content (like 44%) are scarce, and companies need to adjust to the lower grade material (like 42%) to produce stainless-steel. Because chrome is imperishable like other resources, companies are now required to mine deeper to be able to access the required material which increases the cost of extraction and increases safety concerns (Lane *et al.*, 2015:473). With this lower grade chrome, which will contain lower percentage chrome content in a unit, comes new challenges in the beneficiation (processing) of chrome which will be discussed next.

2.7. BENEFICIATION OF CHROME

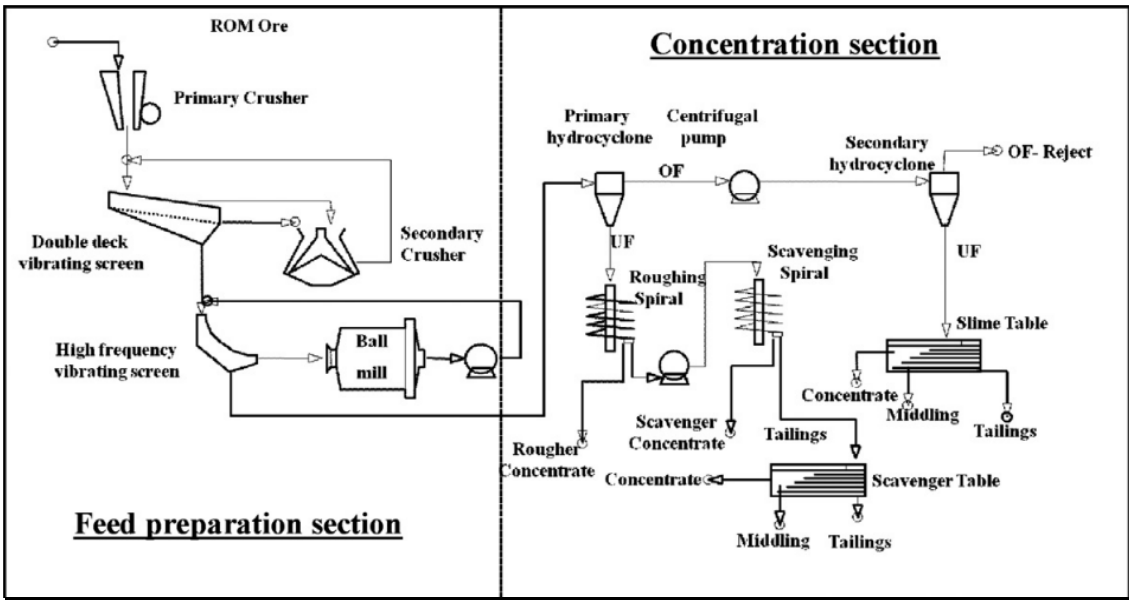
2.7.1 Types of wet processes

There are different ways of processing chrome, for instance, hydro-cyclone, tabling, Wet High-Intensity Magnetic Separation (WHIMS) and flotation methods, each with its speciality regarding size or grade (Das, 2015:335). Hydro-cyclone makes use of the cyclone concept; the tabling-method is a table that shakes the input material and let gravity move the chrome from the rest of the material. WHIMS makes use of water and very high gauze magnets to separate chrome from the rest of the materials, and the flotation method focuses on the concept of floating the material. Spiral, magnetic, flotation and flocculation are four different methods that each specialise in a different feed grade (percentage of the chrome per unit as input material) and particular sizes (Panda *et al.*, 2014:666). Using a combination of these processes are getting more important with the depletion of chrome ore and lower feed grade (Bhandary *et al.*, 2016:1097).

2.7.2 Spiral plant: gravitational process

Two conventional processes making use of gravitational force is spirals and shaking tables (Murthy *et al.*, 2011:377). The concentration section in figure 5 shows that different methods can be used alone or in combination. The feed preparation section is where they crush down the ROM to +-1mm before it is sent to the concentration section (Murthy *et al.*, 2011:377).

Figure 5: General process flow from chrome ROM to chrome concentrate



Source (Murthy *et al.*, 2011:377)

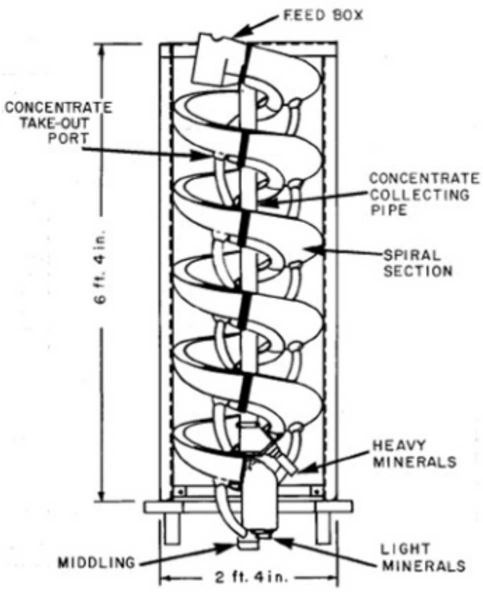
An example of a newly built spiral plant can be seen in figure 6, where the yellow in the top is the spirals, and yellow at the bottom is controls.

Figure 6: Chrome spiral wash plant process

(Stoffberg, 2017:2)

In a production plant the grade of the chrome-ore feed content (input material) as well as the waste of the process, which still contains a percentage of chrome, is different due to different samples and sizes (Das, 2015:336). Chrome, being a heavy metal, is mostly processed using a gravity separation method like a spiral (see figure 7) because it is easy to manage and low on cost (Tripathy & Rama Murthy, 2012:387). The feed box is for the input of the material. The output will be divided into two, heavy mineral like chrome and light mineral being the waste material. There are different points of collection for concentrate, which are the heavy minerals.

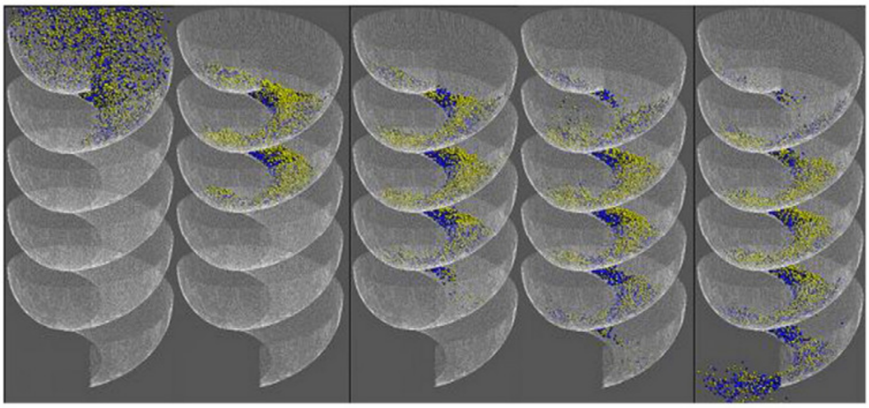
Figure 7: Gravity separation spiral



Source: (Grewal, 2016:18)

To illustrate how particulars of chrome divide in a spiral, figure 8 snapshots the different steps of what theoretically happens in a spiral. The blue represents the heavier mineral, in this case, chrome, while the yellow illustrates the rest of the material.

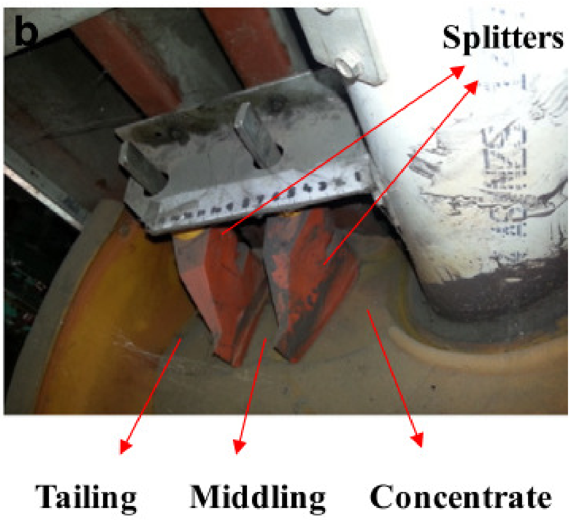
Figure 8: Spiral progress snapshot.



Source: (Mishra & Tripathy, 2010:194)

The success of the spiral process is determined by managing the different variables for the optimum recovery. The variable with the biggest effect is the directing of the splitter position for the required performance (Tripathy & Rama Murthy, 2012:392). Figure 9 illustrates what a splitter is, the function is to split/cut the good material from the rest. The splitter determines what material pass as heavy minerals that will be the product or light minerals that will end of as waste. In other words, the splitter position determines the grade and the management of the position determine optimisation of recovery of chrome. Recovery is referred to as the amount of minerals that can be recovered, either in percentage or ton, from the feed material (Wills & Finch, 2015:10)

Figure 9: Splitter of a Spiral separator



Source: (Dixit *et al.*, 2015:106)

The percentage of the mineral being processed that end up in the waste due to the spiral process is between 15% and 20% (Dixit *et al.*, 2015:105). Therefore the idea is to use the splitter to split the chrome from the waste accurately, but a change in the splitter either creates more or less chrome in the waste (tailing) (Tripathy & Rama Murthy, 2012:392). To be efficient, you want your waste material to contain as little as possible chrome without sacrificing on income. The efficiency can be monitored using the recovery formula which is discussed next.

2.8 RECOVERY FORMULA

Mineral processing requires greater productivity and more recovery from ores (physical chrome product), and this can be done with the correct measurements in place (Bouffard, 2015:140). Integration of metallurgical concepts with accounting principles is needed to improve production (Bascur & Linares, 2006:697). The effectiveness of a spiral is determined by the quality of the input material and the operating conditions. The operating conditions can theoretically determine the maximum efficiency of the spiral depending on the material (Honaker *et al.*, 2007:1315). One of the controls is the mass recovery formula which calculates the mass of the units (tonnes) that can be recovered from the quality and amount of input material (Michaud, 2013:1). The mass recovery formula according to an article on Metallurgy911 (Michaud, 2013:1) is as follow:

$$R = (f-t) / (c-t)$$

Where:

R: Recovery

f: Feed grade in %

This is the % of chrome in the input material.

c: Concentrate grade in %.

The output product that is required, for this study it will be 42% or 44%.

t: Tailings grade in %.

This is the percentage of chrome that is in the material that is wasted.

The above formula is the inversion of the recovery formula and is also known as the yield (Wills & Finch, 2015:10). The variables are feed grade that depends on ROM available and the tailings grade that depends on the efficiency of the plant. The application of the formula is proven in figure 10 when it was tested on a spiral in a controlled environment with coal.

Figure 10: Mass recovery formula applied to coal spiral

Operating conditions derived from the non-linear optimization study to maximize combustible recovery at a desired product ash value for 210 × 44 μm coal cleaning

Feed rate (l/min)	Solids (%)	Splitter (cm)	Desired product ash (%)	Maximum recovery (%)	Mass flow (t/h)
46	13.2	30	12	83.50	0.38
46	14.5	27	13	87.70	0.42
46	15.8	23	14	91.30	0.46
46	17.1	19	15	94.17	0.50
49	16.1	16	16	95.75	0.51
58	14.9	16	17	96.40	0.55
67	13.7	16	18	96.89	0.58
75	12.6	16	19	97.23	0.59
83	11.6	16	20	97.46	0.60
90	10.7	16	21	97.58	0.61

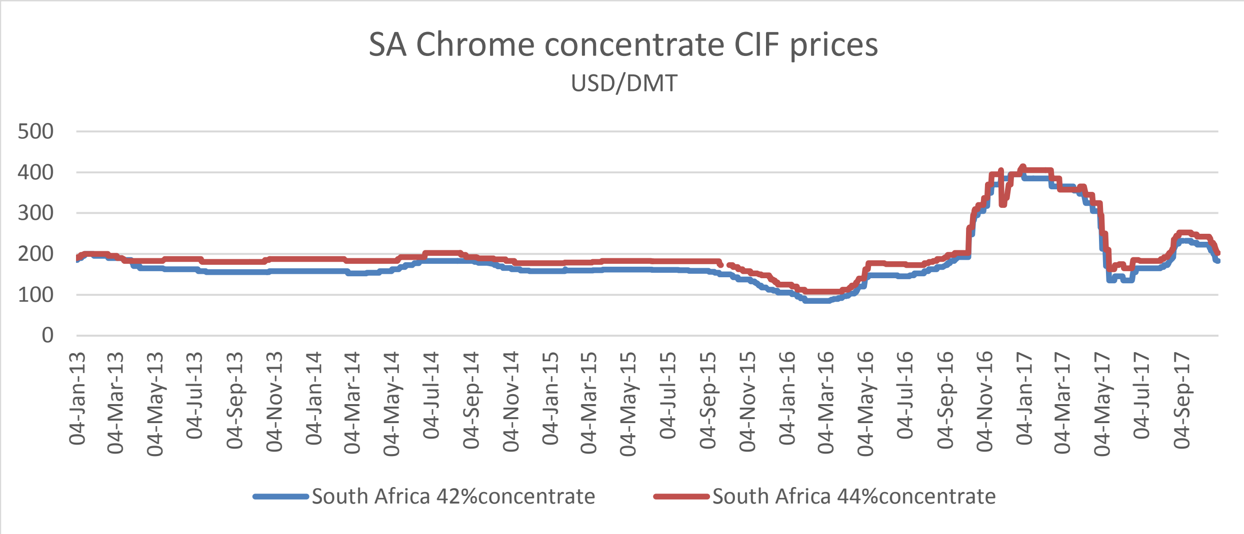
Source: (Honaker *et al.*, 2007:1318)

The table illustrates that with the different feed rate and splitter at a certain position the maximum recovery was calculated by using the solids as input material and desired product ash as output material. The formula is for the optimum theoretical recovery, where in practical controlled cases a deviation of up to 5% was observed (Tripathy & Rama Murthy, 2012:391). The recovery formula provides the quantity of revenue management. Sales as an important variable for price optimisation will be discussed next.

2.9 TOTAL SALES FORMULA

To ensure profitability, there are two tools that are important such as the reaction to price and production planning (Castro *et al.*, 2013:13046). Total sales are determined by the selling price per unit multiplied by the total units sold (Carter, 2017:1). By using the mass recovery ratio, the units can be determined that is needed for the production variable in the equation. The market value of chrome concentrate from South Africa is published on FerroAlloyNet and quoted in United States Dollar (USD). Figure 11 illustrates the prices published from January 2013 until October 2017 for SA 42% and 44% chrome concentrate and the price difference over the years. This defines the price variable that is one of the tools for profitability.

Figure 11: South Africa chrome concentrate market prices 2013-2017 (USD/ dmt unit)



Source: (FerroAlloyNet, 2017)

Chrome prices are determined according to the chrome content within the unit dry metric ton. Figure 11 illustrates the two chrome products required by the demand market namely South Africa 42% concentrate and South Africa 44% concentrate. The price variance between the two products is not constant; this is due to the demand on the High Carbon ferrochrome side and costs (Pan, 2013). If demand increase for the higher grade the price difference will increase as this is a free market. The concept of IDSR inspired the concept of the study since it is based on reacting to changes in market prices (Hadera *et al.*, 2015). For the profitability tool to be combined with the efficiency tool, a balancing tool is needed such as the equilibrium formula.

2.10 EQUILIBRIUM FORMULA

Equilibrium is defined as a state of balance where two points are equal (Oxford, 2017). The model created in this study is for the use of managers in an actual application where there are fewer variables unknown such as the input grade and tailings. For the case, study assumptions are needed where in practice it can be controlled. For the case study, the balance of the two products are determined as a turning point and graphically illustrate when it will be more beneficial to produce which product.

Therefore, the equilibrium points or point of balance in a spiral plant is when the total possible income of 44% concentrate in sales is equal to the total possible income of sales of 42% concentrate.

2.11 SUMMARY

Chrome ore market is a free market with South Africa as its biggest supplier and China as its biggest buyer. The three formulas namely mass recovery ratio, total sales formula and the equilibrium formula, were discussed as tools that will be used to create a model that can help companies in the chrome processing industry with CSR. To determine when it would be more beneficial to produce a concentrate with the content of 44% chrome or 42% chrome concentrate product, dependant on the different variables, for instance, input grade, an empirical investigation will be performed in the next section in the form of a case study.

CHAPTER 3: EMPIRICAL STUDY

3.1 INTRODUCTION

This study follows a case study as research method because it explores the application of the model in an actual environment (Zainal, 2017:4). The case study can apply the model to different scenarios considering the different variables that can be found in a spiral plant. For the price evaluation of different grades of chrome, a model will be developed in this chapter. Currently in practise these formulas are used but not in combination. The principle might be in use but no literature study on this type or similar model is available. By creating a point of equilibrium in the model, it will illustrate the turning point in the spiral plant. This will be illustrated in a case study by applying different scenarios to different variables.

3.2 RESEARCH METHOD

To use a case study as research method, the following three issues needs to be addressed namely theory, reliability and validity to support why a case study is a valuable research method (Flyvbjerg, 2006:221). The theory for the model that is developed was discussed in chapter two. This support the fundamentals of the model for the case study that will be applied and therefore is not just generalisation based on assumptions. The reliability of the case study is dependent on the model. If applied accurately it is reliable. According to Flyvbjerg, a case study can be utilised to test different hypothesis by creating different scenarios (Flyvbjerg, 2006:223). But the outcome of each scenario is based on real-life applications and therefore is more reliable and valid. The third issue addresses validity, where the model is applied to an actual case where a manager needs to make a decision. This illustrates the validity of the model in chapter 4. The validity of the case study will be illustrated by how the same conclusion can be made when the different scenarios were applied in the case study.

The following steps were created by Eisenhardt and adapted by Cronin for building theory when using a case study as a research method and will be discussed how it was applied (Cronin, 2014:24).

Design:

- Step 1 is initiated by defining the research question. This was done in chapter one when the following research question was identified: Is it better to produce a chrome concentrate of 42% rather than 44% at different sales prices and input grades of the material?
- Step 2 is to identify cases that aren't theory or hypothesis. Three scenarios were identified regarding the tailings that will be applied to different price variables and feed material.

- Step 3 is to craft the instrument. This will be done in chapter 3 by creating a model from the literature review done in chapter 2.

Fieldwork:

- Entering the field is step 4. As part of chapter 2 in the literature review, the field was entered in the form of gathering the data regarding chrome and the beneficiation process and total sales prices, as well as discussing the formulas that are needed to create the model.

Analysing data:

- Step 5 is applied in chapter 3 when the data and model are applied in the form of the case study by applying the model to the different scenarios. The shaping of the hypothesis for step 6 will be done when the application of the model is applied to the different scenarios and variables created, which will be graphically demonstrated.

Comparative literature:

- Step 7 was defined as the enfolding of literature; this is where the value of this study is. It is a combination of supporting literature on a theory by creating the model based on the theory. There is no conflicting literature on the results of the case study since the model is a new concept based on different formulas.

Closure:

- The last step is to reach a conclusion which will be done in the final chapter.

The case study is more for exploratory purposes as it will apply the model that will be created in this chapter to different scenarios to see the reaction and test the model. It is a form of researching real-world application while being realistic (Runeson & Höst, 2008:131).

3.3 DEVELOPING A MODEL FOR APPLICATION IN THE CASE STUDY

3.3.1 Data collection

The data collected for this study involves the examination of the reported Cost Insurance Freight (CIF) prices (CIF is the price including cost, insurance and freight to the place of delivery) for the two different products and the variation in price difference. The purpose is not to focus on the market prices but rather determine the equilibrium for the different prices with different input material.

The prices collected was from 4 January 2013 to 31 October 2017 from FerroAlloyNet, a website that publishes the prices that China customers paid CIF for South Africa chrome concentrate (FerroAlloyNet, 2017). Part of the gathering of data was the gathering of the formulas that will be used to create the model.

3.3.2 Applying the mass recovery formula to total sales

The three formulas identified in Chapter 2 that will be used in the creation of the model are the mass recovery-, sales- and equilibrium formula. These are the most commonly used formulas in practise. The following assumptions will be made:

Product 1: South Africa 44% chrome concentrate will be referred to as X.

Product 2: South Africa 42% chrome concentrate will be referred to as Y.

Equilibrium will, therefore, be when X=Y.

The sales prices of the two that will be taken into consideration to determine the equilibrium point for produced tonnages at market value. The sales formula (price multiplied by units) will change the formula as follows:

Price of X multiply Units of X= Price of Y multiply Units of Y

$$P(X) \times U(X) = P(Y) \times U(Y)$$

The price can be collected from the market and what they are willing to pay. The units is affected by the mass recovery formula therefore the formula develops further into:

$$P(X) \times R(X) = P(Y) \times R(Y)$$

$$P(X) \times (f-t)/(X-t) = P(Y) \times (f-t)/ (Y-t)$$

This provides us with the equilibrium point. The formula used in this study will be as follows:

$$M= [P(X) \times (f-t)/(X-t)] – [P(Y) \times (f-t)/ (Y-t)]$$

- If the answer is greater than 0, it is better to produce a 44% chrome concentrate.
- If the answer is equal to zero, it is the equilibrium point, and both products are beneficial to produce.
- If the answer is less than 0, it is more beneficial to produce a 42% concentrate.

Based on the previous formulas and the developing of the model it would now be applied through a case study.

3.4 APPLYING THE MODEL THROUGH A CASE STUDY

For the case study, three scenarios have been investigated with two different assumptions of the tailings and three price variances. To apply the model developed in chapter 3.2, a break down into different steps have been illustrated by first calculating the mass recovery for different input material of each scenario, followed by the different prices to calculate the equilibrium point.

3.3.1 Scenario 1: The waste percentage chrome in the tailings is the same

For this scenario, the mass recovery was calculated on a range of different input material grades with the assumption that for both products the waste percentage of chrome in the tailings was the same. Table 1 illustrates the mass recovery assuming that the tailings will be 15% while table 2 applies the assumption that the tailings will be 20%. From table 1 it is clear that the mass recovery for a higher grade concentrate, in this case, 44%, is lower than a 42% concentrate. Also the higher the chrome in the input material, the bigger is the difference between the mass recovery of the two products

Table 1: Mass recovery for different input grades with consistent tailings of 15%.

Tailings 15%:	42%	44%
Cr_2O_3 Input	%Mass Rec	%Mass Rec
48%	122	114
47%	119	110
46%	115	107
45%	111	103
44%	107	100
43%	104	97
42%	100	93
41%	96	90
40%	93	86
39%	89	83
38%	85	79
37%	81	76
36%	78	72
35%	74	69
34%	70	66
33%	67	62
32%	63	59
31%	59	55
30%	56	52
29%	52	48
28%	48	45
27%	44	41
26%	41	38
25%	37	34
24%	33	31
23%	30	28
22%	26	24
21%	22	21
20%	19	17
19%	15	14
18%	11	10
17%	7	7
16%	4	3
15%	-0	-0

With the feed material at 48% grade, referring to the chrome mass, it can be concluded from table 1 that 122% can be recovered when producing a 42% concentrate while only 114% can be recovered when producing a 44%. The difference between the mass recovery for the two products reduces as the feed material grade reduces. Therefore with 26% grade feed material, only 41% can be recovered when producing a 42% concentrate and 38% when producing a 44% concentrate.

Table 2: Mass recovery for different input grades with consistent tailings of 20%.

Tailings: 20%	**42%**	**44%**
Cr2O3 Input	%Mass Rec	%Mass Rec
48%	127	117
47%	123	113
46%	118	108
45%	114	104
44%	109	100
43%	105	96
42%	100	92
41%	95	88
40%	91	83
39%	86	79
38%	82	75
37%	77	71
36%	73	67
35%	68	62
34%	64	58
33%	59	54
32%	55	50
31%	50	46
30%	45	42
29%	41	37
28%	36	33
27%	32	29
26%	27	25
25%	23	21
24%	18	17
23%	14	12
22%	9	8
21%	5	4
20%	-0	-0

Table 2 illustrates that with feed material containing 48% chrome the mass chrome recovery with 20% in the tailings is 127% when producing a 42% concentrate. When producing a 44% concentrate, the mass recovery is 117%. This is a 10% difference in recovery between producing the two products, 2% more than in table 1 when there were 15% in the tailings. When the feed material contains only 26% chrome, the mass recovery is 27% when producing a 42% concentrate and 25% when producing a 44% concentrate. With the higher grade more can be recovered with 20% in the tailings than with 15% in the tailings but with the lower feed material less can be recovered. When producing a 42% concentrate, 14% less chrome mass can be recovered when the tailings are 20% than when the tailings are 15% as illustrated in table 1.

By applying the three-price variables, table 3 illustrates the price for 42% concentrate equilibrium is reached with a 44% concentrate, assuming there is 15% chrome in the tailings. These are the turning point prices where a plant can either produce a 42% concentrate or a 44% concentrate. By applying the price difference, the same total sales income will be received for both products.

Table 3: Equilibrium price table for 15% in the waste.

			Equilibrium price applying:		
Tailings 15%:	**42%**	**44%**	Price difference that 44% is more		
Cr2O3 Input	%Mass Rec	%Mass Rec	$2.50	$20	$40
48%	122	114	$ 34	$ 270	$ 540
47%	119	110	$ 34	$ 270	$ 540
46%	115	107	$ 34	$ 270	$ 540
45%	111	103	$ 34	$ 270	$ 540
44%	107	100	$ 34	$ 270	$ 540
43%	104	97	$ 34	$ 270	$ 540
42%	100	93	$ 34	$ 270	$ 540
41%	96	90	$ 34	$ 270	$ 540
40%	93	86	$ 34	$ 270	$ 540
39%	89	83	$ 34	$ 270	$ 540
38%	85	79	$ 34	$ 270	$ 540
37%	81	76	$ 34	$ 270	$ 540
36%	78	72	$ 34	$ 270	$ 540
35%	74	69	$ 34	$ 270	$ 540
34%	70	66	$ 34	$ 270	$ 540
33%	67	62	$ 34	$ 270	$ 540
32%	63	59	$ 34	$ 270	$ 540
31%	59	55	$ 34	$ 270	$ 540
30%	56	52	$ 34	$ 270	$ 540
29%	52	48	$ 34	$ 270	$ 540
28%	48	45	$ 34	$ 270	$ 540
27%	44	41	$ 34	$ 270	$ 540
26%	41	38	$ 34	$ 270	$ 540
25%	37	34	$ 34	$ 270	$ 540
24%	33	31	$ 34	$ 270	$ 540
23%	30	28	$ 34	$ 270	$ 540
22%	26	24	$ 34	$ 270	$ 540
21%	22	21	$ 34	$ 270	$ 540
20%	19	17	$ 34	$ 270	$ 540
19%	15	14	$ 34	$ 270	$ 540
18%	11	10	$ 34	$ 270	$ 540
17%	7	7	$ 34	$ 270	$ 540
16%	4	3	$ 34	$ 270	$ 540

With a price difference of $2.50 more for a 44% concentrate, the equilibrium point is at $34 for a 42% concentrate. When the price difference is $20 more for a 44% concentrate, the equilibrium point is at $270 for a 42% concentrate. When the price difference is $40 more for a 44% concentrate, the equilibrium point is at $540 for a 42% concentrate. This illustrates that the equilibrium price increase in relation to the price difference. The more the price difference is, the higher the turning point is for when it is more beneficial to produce a 42% concentrate.

Table 4 illustrates that with the higher tailings of 20%, the equilibrium prices are lower for a 42% concentrate applying the different price scenarios.

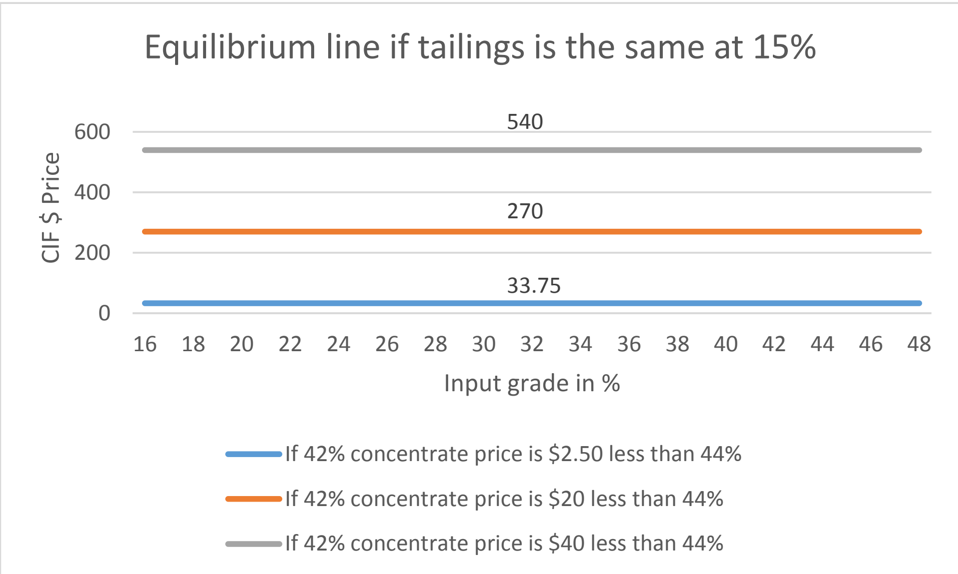
Table 4: Equilibrium price table for 20% in the waste.

			Equilibrium price applying:		
Tailings: 20%	**42%**	**44%**	Price difference that 44% is more		
Cr2O3 Input	%Mass Rec	%Mass Rec	$2.50	$20	$40
48%	127	117	$ 28	$ 220	$ 440
47%	123	113	$ 28	$ 220	$ 440
46%	118	108	$ 28	$ 220	$ 440
45%	114	104	$ 28	$ 220	$ 440
44%	109	100	$ 28	$ 220	$ 440
43%	105	96	$ 28	$ 220	$ 440
42%	100	92	$ 28	$ 220	$ 440
41%	95	88	$ 28	$ 220	$ 440
40%	91	83	$ 28	$ 220	$ 440
39%	86	79	$ 28	$ 220	$ 440
38%	82	75	$ 28	$ 220	$ 440
37%	77	71	$ 28	$ 220	$ 440
36%	73	67	$ 28	$ 220	$ 440
35%	68	62	$ 28	$ 220	$ 440
34%	64	58	$ 28	$ 220	$ 440
33%	59	54	$ 28	$ 220	$ 440
32%	55	50	$ 28	$ 220	$ 440
31%	50	46	$ 28	$ 220	$ 440
30%	45	42	$ 28	$ 220	$ 440
29%	41	37	$ 28	$ 220	$ 440
28%	36	33	$ 28	$ 220	$ 440
27%	32	29	$ 28	$ 220	$ 440
26%	27	25	$ 28	$ 220	$ 440
25%	23	21	$ 28	$ 220	$ 440
24%	18	17	$ 28	$ 220	$ 440
23%	14	12	$ 28	$ 220	$ 440
22%	9	8	$ 28	$ 220	$ 440
21%	5	4	$ 28	$ 220	$ 440

With a price difference of $2.50 more for a 44% concentrate, the equilibrium point is at $28 for a 42% concentrate, $6 less than table 3. When the price difference is $20 more for a 44% concentrate, the equilibrium point is at $220 for a 42% concentrate; this is $50 less than table 3. When the price difference is $40 more for a 44% concentrate, the equilibrium point is at $440 for a 42% concentrate, a $100 less than table 3. This illustrates that the equilibrium price is lower when the tailings are higher.

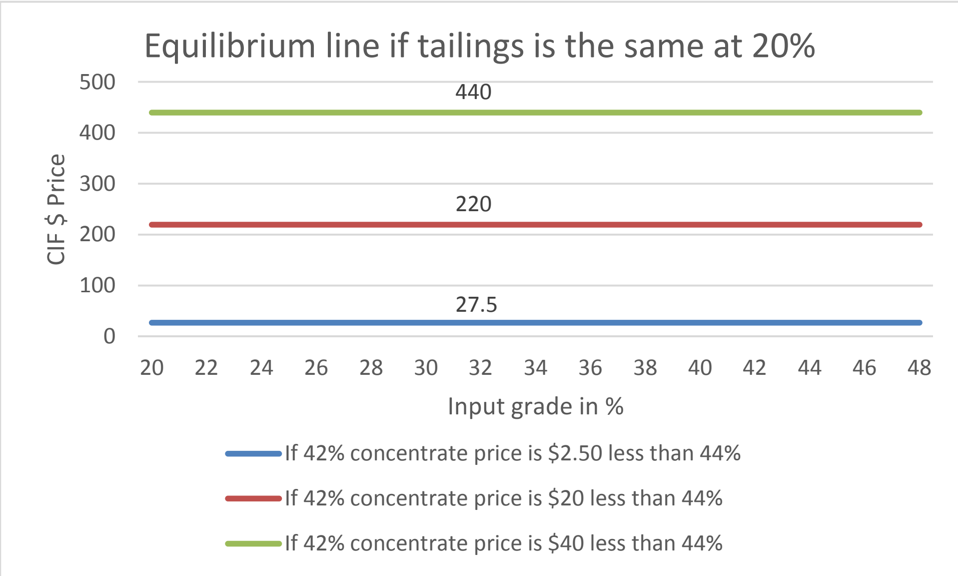
Figure 12 illustrates Scenario 1 with 15% in the tailings. The light blue/bottom line represents the equil line, meaning if 42% concentrate price is $33.75 with a price difference of $2.50 more for a 44%. At this point, it doesn't matter which product the spiral produce with any input grade. If the price goes above $33.75 with $2.50 price difference, it is better to produce a 42%. As the price difference increases, the equilibrium price also moves higher. Therefore the equilibrium point for $20 price difference is $270 for a 42% concentrate and $540 when the price difference is $40. With the conclusion that above those prices it is better to produce a 42% concentrate, of which the opposite is also true (i.e. below those prices).

Figure 12: Equilibrium line if the tailings is the same at 15% as per table 3



The same applies to figure 13 just with different prices. With a price difference of $2.50, it is now more beneficial to produce a 42% when the selling price is above $27.50. When the selling price is above $220 and the price difference is $20 or when the price is above $440, and the price difference is $40, it is more beneficial to produce a 42% concentrate. Only when the prices are below the line, is it more beneficial to produce a 44% concentrate, depending on the price difference. Therefore it will be more beneficial to produce a 42% concentrate with 20% in the tailings more of the times than it would be with a 15% in the tailings with the lower equilibrium line.

Figure 13: Equilibrium line if the tailings is the same at 20% as per table 3



3.3.2 Scenario 2: The waste percentage chrome in the tailings is 2% different.

Applying the same assumptions for scenario 2 as was made for scenario 1 that there is the assumption of 15% chrome in the tailings when producing a 42% concentrate or the assumption is changed to where there is 20% chrome in the tailings with the only difference that it will be assumed that there will be 2% more in the tailings of the 44% chrome concentrate.

The change in the assumption for the additional percentage chrome in the tailings for a 44% concentrate is based on the splitter position that is being changed as discussed in the literature review. A 2% was assumed as this is the percentage difference between the two products. Table 5 illustrates the mass recovery, applying the assumption of 2% difference for the two different tailings percentage assumptions.

Table 5: Mass recovery with the assumption of 15% in tailings for 42% concentrate with a 2% difference in the tailings.

Product:	**42%**	**44%**
Tailings:	**15%**	**17%**
Cr2O3 Input	%Mass Rec	%Mass Rec
48%	122	115
47%	119	111
46%	115	107
45%	111	104
44%	107	100
43%	104	96
42%	100	93
41%	96	89
40%	93	85
39%	89	81
38%	85	78
37%	81	74
36%	78	70
35%	74	67
34%	70	63
33%	67	59
32%	63	56
31%	59	52
30%	56	48
29%	52	44
28%	48	41
27%	44	37
26%	41	33
25%	37	30
24%	33	26
23%	30	22
22%	26	19
21%	22	15
20%	19	11
19%	15	7
18%	11	4

By applying the assumption that the tailings contain 15% when producing a 42% concentrate and contain 17% when producing a 44% concentrate, table 5 indicate the mass recovery for each of the different feed material grades. When producing a 42% concentrate, 7 to 8% more chrome mass can be recovered than can be recovered when producing a 44% concentrate. The lower the chrome is in the feed material, the lower the recovery become. For each percentage change of chrome in the feed material, there is a change of between 3-4% for mass recovery.

Table 6: Mass recovery with the assumption of 20% in tailings for 42% concentrate with a 2% difference in the tailings.

Product:	42%	44%
Tailings:	20%	22%
Cr2O3 Input	%Mass Rec	%Mass Rec
48%	127	118
47%	123	114
46%	118	109
45%	114	105
44%	109	100
43%	105	95
42%	100	91
41%	95	86
40%	91	82
39%	86	77
38%	82	73
37%	77	68
36%	73	64
35%	68	59
34%	64	55
33%	59	50
32%	55	45
31%	50	41
30%	45	36
29%	41	32
28%	36	27
27%	32	23
26%	27	18
25%	23	14
24%	18	9
23%	14	5

By applying the assumption that the tailings contain 20% when producing a 42% concentrate and contain 22% when producing a 44% concentrate, table 6 indicate the mass recovery for each of the different feed material grades. When producing a 42% concentrate, 9-10% more chrome mass can be recovered than can be recovered when producing a 44% concentrate. The lower the chrome is in the feed material, the lower the recovery become. For each percentage change of chrome in the feed material, there is a change of between 4-5% for mass recovery.

The change in mass recovery due to change in tailings is illustrated in table 5 and 6 that applies scenario 2 which assumes a 2% difference in tailings. When the tailings are higher the difference in mass recovery also increases. The change in mass recovery regarding 1% change in feed material also increases. Indicating that the change in tailings is creating more volatility in recovery.

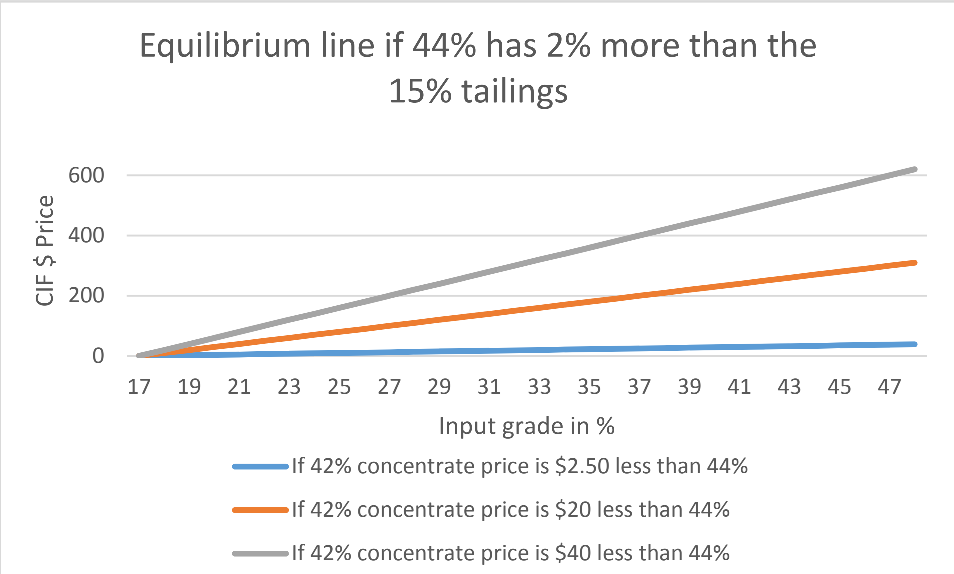
Table 7: Equilibrium price table for 15% in the tailings for 42% and 17% in the tailings for 44% chrome concentrate.

Product:	**42%**	**44%**	Equilibrium price applying:		
Tailings:	**15%**	**17%**	Price difference that 44% is more		
Cr2O3 Input	%Mass Rec	%Mass Rec	$2.50	$20	$40
48%	122	115	$ 39	$ 310	$ 620
47%	119	111	$ 37	$ 300	$ 600
46%	115	107	$ 36	$ 290	$ 580
45%	111	104	$ 35	$ 280	$ 560
44%	107	100	$ 34	$ 270	$ 540
43%	104	96	$ 32	$ 260	$ 520
42%	100	93	$ 31	$ 250	$ 500
41%	96	89	$ 30	$ 240	$ 480
40%	93	85	$ 29	$ 230	$ 460
39%	89	81	$ 27	$ 220	$ 440
38%	85	78	$ 26	$ 210	$ 420
37%	81	74	$ 25	$ 200	$ 400
36%	78	70	$ 24	$ 190	$ 380
35%	74	67	$ 22	$ 180	$ 360
34%	70	63	$ 21	$ 170	$ 340
33%	67	59	$ 20	$ 160	$ 320
32%	63	56	$ 19	$ 150	$ 300
31%	59	52	$ 18	$ 140	$ 280
30%	56	48	$ 16	$ 130	$ 260
29%	52	44	$ 15	$ 120	$ 240
28%	48	41	$ 14	$ 110	$ 220
27%	44	37	$ 13	$ 100	$ 200
26%	41	33	$ 11	$ 90	$ 180
25%	37	30	$ 10	$ 80	$ 160
24%	33	26	$ 9	$ 70	$ 140
23%	30	22	$ 8	$ 60	$ 120
22%	26	19	$ 6	$ 50	$ 100
21%	22	15	$ 5	$ 40	$ 80
20%	19	11	$ 4	$ 30	$ 60
19%	15	7	$ 3	$ 20	$ 40
18%	11	4	$ 1	$ 10	$ 20

Table 7 applies the price difference for scenario 2 with the assumption of 15% chrome in the tailings when producing a 42% chrome concentrate and 17% chrome in the tailings when producing a 44% chrome concentrate. The relationship between the price differences is the same for the difference in equilibrium prices. Therefore the equilibrium price increase in the same relationship as the price increase.

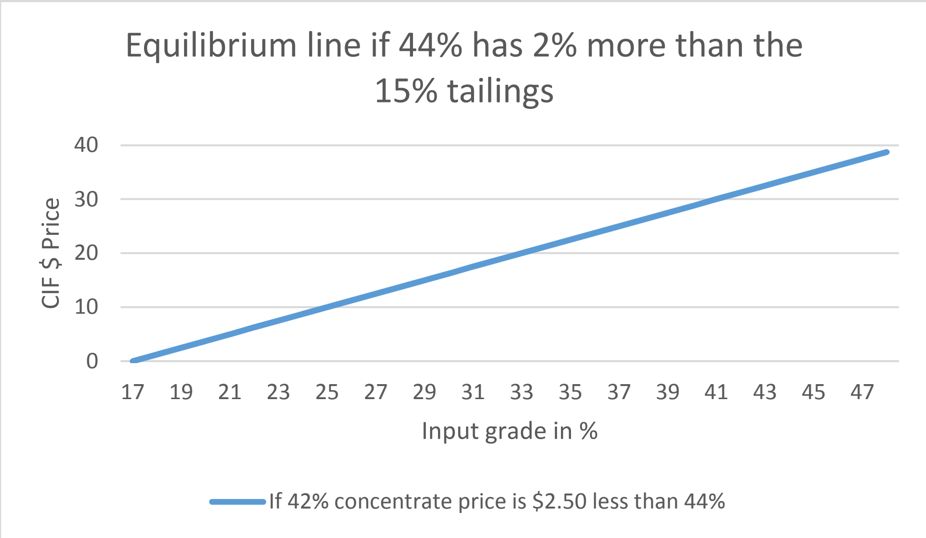
Due to the difference in the tailings and input grades the equilibrium prices changed and visually gained a slope as can be seen from figure 14. As the price difference increase, the equilibrium line changes. The input grade will, therefore, be relevant when a decision is made on the basis of the equilibrium line.

Figure 14: Equilibrium line if 44% has 2% more chrome than the 15% tailings as per table 7



The higher the price difference, the steeper the equilibrium line as can be seen from figure 14. This indicates in table 7 that the higher the price difference between the two products combined with the higher the input material chrome content is, the higher is the equilibrium point is. To better see the effect of the change in 2% tailings, the price variable of $2.50 will be illustrated graphically. Figure 15 illustrates the price variable of $2.50 applied to the 15% of the waste material for a 42% chrome concentrate and 17% for a 44% chrome concentrate.

Figure 15: Equilibrium line if 44% has 2% more chrome than the 15% tailings with a price difference of $2.50 as per table 7



With a price difference of $2.50, if the selling price is above $40 it will be more beneficial to produce a 42% chrome concentrate. If the selling price is $20, the input grade of 33% will be the turning point. Spiral plants with feed material above 33% should produce a 44%, spiral plants with feed material below 33% should produce a 42%. The equilibrium line in figure 15 indicates that when there is a price difference of $2.50, and there is a difference in tailings of 2% more when producing a 44% chrome concentrate, it is more beneficial to produce a 42% concentrate when the price and input material chrome grade is above the blue line.

Table 8 is applying the same scenario to a 2% difference in the tailings, but instead of 15% in the tailings when producing a 42% chrome concentrate, there is 20% in the tailings. With the assumption of a two percent difference, the 44% chrome concentrate will then have 22% chrome in the tailings. This is then applied to the three price differences namely $2.50; $20 and $40 for each different input material chrome grade.

Table 8: Equilibrium price table for 20% in the tailings for 42% and 22% in the tailings for 44% chrome concentrate.

Product:	**42%**	**44%**	Equilibrium price applying:		
Tailings:	**20%**	**22%**	Price difference that 44% is more		
Cr2O3 Input	%Mass Rec	%Mass Rec	$2.50	$20	$40
48%	127	118	$ 33	$ 260	$ 520
47%	123	114	$ 31	$ 250	$ 500
46%	118	109	$ 30	$ 240	$ 480
45%	114	105	$ 29	$ 230	$ 460
44%	109	100	$ 28	$ 220	$ 440
43%	105	95	$ 26	$ 210	$ 420
42%	100	91	$ 25	$ 200	$ 400
41%	95	86	$ 24	$ 190	$ 380
40%	91	82	$ 23	$ 180	$ 360
39%	86	77	$ 21	$ 170	$ 340
38%	82	73	$ 20	$ 160	$ 320
37%	77	68	$ 19	$ 150	$ 300
36%	73	64	$ 18	$ 140	$ 280
35%	68	59	$ 16	$ 130	$ 260
34%	64	55	$ 15	$ 120	$ 240
33%	59	50	$ 14	$ 110	$ 220
32%	55	45	$ 13	$ 100	$ 200
31%	50	41	$ 11	$ 90	$ 180
30%	45	36	$ 10	$ 80	$ 160
29%	41	32	$ 9	$ 70	$ 140
28%	36	27	$ 8	$ 60	$ 120
27%	32	23	$ 6	$ 50	$ 100
26%	27	18	$ 5	$ 40	$ 80
25%	23	14	$ 4	$ 30	$ 60
24%	18	9	$ 3	$ 20	$ 40
23%	14	5	$ 1	$ 10	$ 20

From table 8 it is clear that the equilibrium prices also increase with the higher input material. The higher the price difference, the higher the equilibrium line. When comparing to table 7, the prices for the lower input material is the same, but as the input material chrome content increase, the equilibrium line for the two start to vary with a lower equilibrium price when there is more chrome in the tailings. In figure 16, table 8 is graphically illustrated. The equilibrium price is lower than in figure 14 that illustrates the price difference when the chrome content in the tailings is lower. Figure 16 contains a slope as equilibrium price increase with the higher input material.

Figure 16: Equilibrium line if the 44% has 2% more chrome than the 20% tailings as per table 8

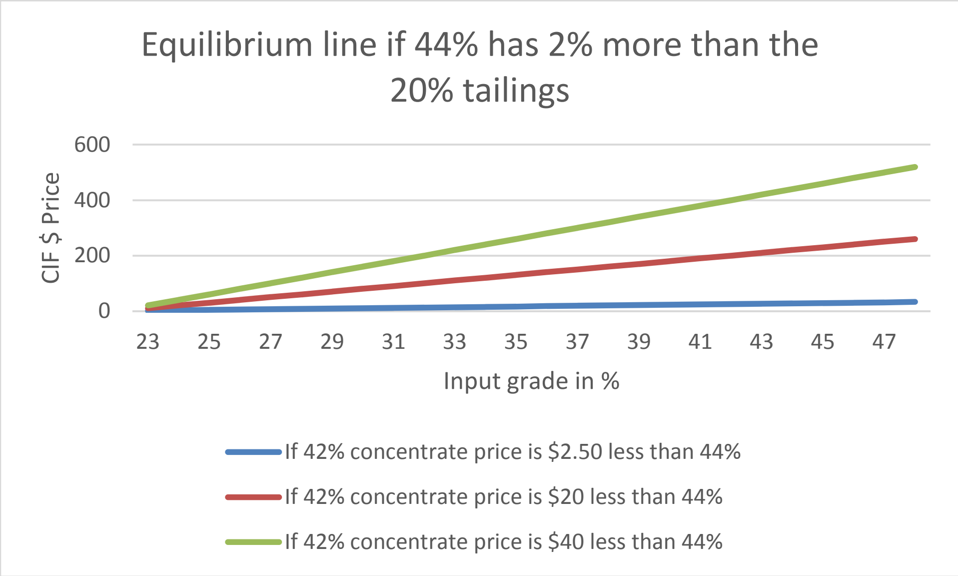
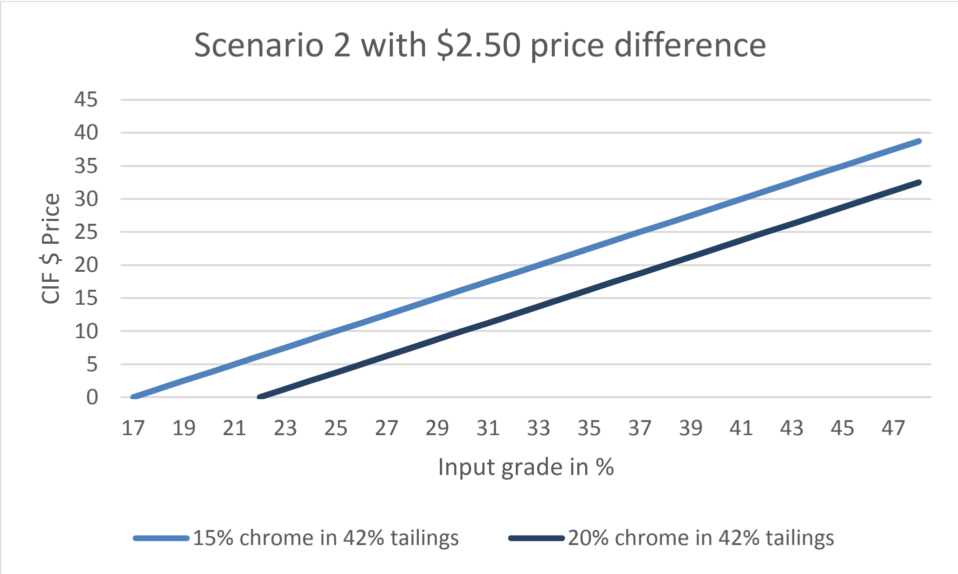


Figure 16 indicates the equilibrium price for when there is 20% chrome in the tailings when producing a 42% chrome concentrate and 22% chrome in the tailings when producing a 44% chrome concentrate. Above the line is when it is more beneficial to produce a 42% chrome concentrate when considering the price and input material chrome content. The different lines represent different price variances.

Figure 17 illustrates a more detailed difference by comparing the equilibrium line for when there is a price difference of $2.50, and this is applied to when there is 15% chrome in the tailings when producing a 42% chrome concentrate compared to when there is 20% chrome in the tailings when producing a 42% chrome concentrate. This was illustrated in table 7 and 8.

Figure 17: Comparison between equilibrium line for when there is 15% in tailings for 42% and when there is 20% in tailings for 42% based on Scenario 2 with a price difference of $2.50



From figure 17 the change in tailings is clearly illustrated with the two different equilibrium lines. The higher the tailings, the lower the equilibrium price for the same input material. The equilibrium lines that is represented in figure 17 indicate that above the line it is more beneficial to produce a 42% chrome concentrate than a 44% chrome concentrate by applying the variables of Scenario 2 regarding the chrome content in the tailings. For the same input material, at a higher price than the equilibrium price (the blue line) it is more beneficial to produce 42% concentrate.

3.3.3 Scenario 3: The waste percentage chrome in the tailings are 5% more for the 44%

Using the variable of 5% more wastage of chrome material in the tailings when producing a 44% chrome concentrate was applied as the study suggested that a change in the process can cause a 5% variable. This scenario illustrates why control is important as the effect is a lot bigger with the change of 5%.

Table 9 indicates the effect on the mass recovery for the different feed material chrome content by changing the percentage of chrome in the tailings to 5% more when producing a 44% concentrate than the assumption of the tailings of 42% concentrate at 15%.

Table 9: Mass recovery for different input grades with 5% more in the tailings for 44% chrome concentrate when there is 15% chrome in the tailings when producing a 42% chrome concentrate.

Product:	**42%**	**44%**
Tailings:	**15%**	**20%**
Cr2O3 Input	%Mass Rec	%Mass Rec
48%	122	117
47%	119	113
46%	115	108
45%	111	104
44%	107	100
43%	104	96
42%	100	92
41%	96	88
40%	93	83
39%	89	79
38%	85	75
37%	81	71
36%	78	67
35%	74	62
34%	70	58
33%	67	54
32%	63	50
31%	59	46
30%	56	42
29%	52	37
28%	48	33
27%	44	29
26%	41	25
25%	37	21
24%	33	17
23%	30	12
22%	26	8

The difference in the mass recovery when there is a 5% variance in the tailings is more than with table 5 when there was only a 2% variance. The difference in mass recovery when producing a 44% chrome concentrate with 20% in the tailings is higher with the lower grade feed material but the variance decreases with the higher input material when compared to table 5. With the 5% variance in tailings, less chrome can be recovered.

Table 10 indicates the effect on the mass recovery for the different feed material chrome content by changing the percentage of chrome in the tailings to 5% more when producing a 44% concentrate than the assumption of the tailings of 42% concentrate at 20%.

Table 10: Mass recovery for different input grades with 5% more in the tailings for a 44% chrome concentrate when there is 20% chrome in the tailings when producing a 42% chrome concentrate.

Product:	**42%**	**44%**
Tailings:	**20%**	**25%**
Cr2O3 Input	%Mass Rec	%Mass Rec
48%	127	121
47%	123	116
46%	118	111
45%	114	105
44%	109	100
43%	105	95
42%	100	89
41%	95	84
40%	91	79
39%	86	74
38%	82	68
37%	77	63
36%	73	58
35%	68	53
34%	64	47
33%	59	42
32%	55	37
31%	50	32
30%	45	26
29%	41	21
28%	36	16
27%	32	11
26%	27	5

The difference in the mass recovery when there is a 5% variance in the tailings is more than with table 36 when there was only a 2% variance. The difference in mass recovery when producing a 44% chrome concentrate with 25% in the tailings is higher with the lower grade feed material but the variance decrease with the higher input material when compared to table 5. With the 5% variance in tailings, less chrome can be recovered.

Applying the mass recovery from table 9 to different price variables for Scenario 3, table 11 indicates the equilibrium point for when 42% concentrate has 15% in the tailings, and 44% concentrate has 20% chrome content in the tailings.

Table 11: Equilibrium price table for 15% in the tailings for 42% and 20% in the tailings for 44% chrome concentrate.

Product:	**42%**	**44%**	Equilibrium price applying:		
Tailings:	**15%**	**20%**	Price difference that 44% is more		
Cr2O3 Input	%Mass Rec	%Mass Rec	$2.50	$20	$40
48%	122	117	$ 53	$ 420	$ 840
47%	119	113	$ 47	$ 374	$ 748
46%	115	108	$ 42	$ 334	$ 669
45%	111	104	$ 38	$ 300	$ 600
44%	107	100	$ 34	$ 270	$ 540
43%	104	96	$ 30	$ 244	$ 487
42%	100	92	$ 28	$ 220	$ 440
41%	96	88	$ 25	$ 199	$ 398
40%	93	83	$ 23	$ 180	$ 360
39%	89	79	$ 20	$ 163	$ 326
38%	85	75	$ 18	$ 147	$ 295
37%	81	71	$ 17	$ 133	$ 266
36%	78	67	$ 15	$ 120	$ 240
35%	74	62	$ 14	$ 108	$ 216
34%	70	58	$ 12	$ 97	$ 194
33%	67	54	$ 11	$ 87	$ 173
32%	63	50	$ 10	$ 77	$ 154
31%	59	46	$ 9	$ 68	$ 137
30%	56	42	$ 8	$ 60	$ 120
29%	52	37	$ 7	$ 52	$ 105
28%	48	33	$ 6	$ 45	$ 90
27%	44	29	$ 5	$ 38	$ 76
26%	41	25	$ 4	$ 32	$ 64
25%	37	21	$ 3	$ 26	$ 51
24%	33	17	$ 3	$ 20	$ 40
23%	30	12	$ 2	$ 15	$ 29
22%	26	8	$ 1	$ 9	$ 19

The equilibrium prices for producing a 42% chrome concentrate with the different price variables, when compared to table 7, start out lower but increase more with the higher feed material. Above 44% feed material, the equilibrium price is higher than in table 7. This is graphically represented in figure 18 with the higher input grade, the higher the equilibrium price, but less gradually than Scenario 2.

Figure 18: Equilibrium line if 44% concentrate has 5% more chrome in tailings as per table 8

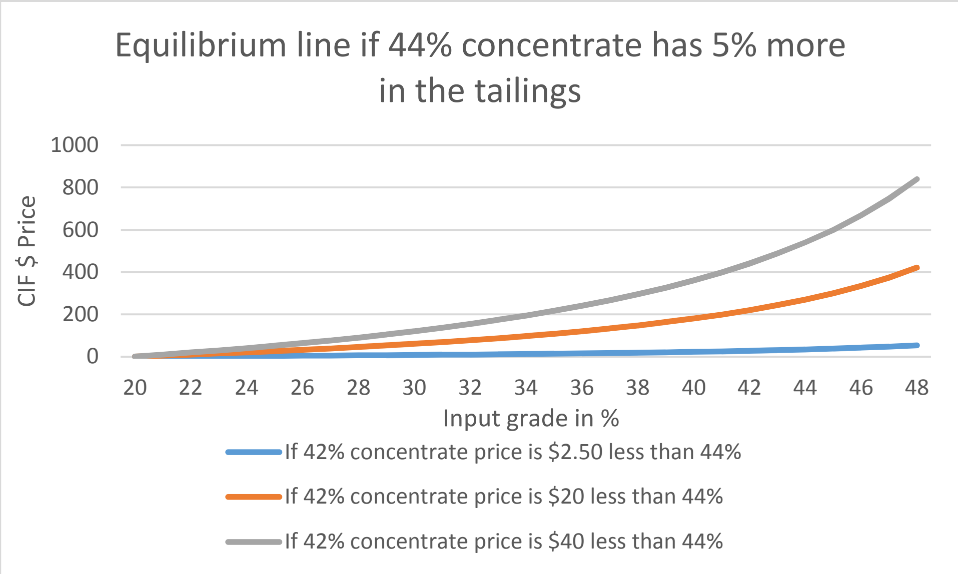


Figure 18 illustrates that with 15% of the tailings of the 42% concentrate while 20% in the tailings of 44% lower the equilibrium prices. With the lower input material up to a higher variety, it is most likely to be more beneficial to produce a 42% concentrate depending on the price.

Table 12: Equilibrium price table for 20% in the tailings for 42% and 25% in the tailings for 44% chrome concentrate.

Product:	**42%**	**44%**	Equilibrium price applying:		
Tailings:	**20%**	**25%**	Price difference that 44% is more		
Cr2O3 Input	%Mass Rec	%Mass Rec	$2.50	$20	$40
48%	127	121	$ 49	$ 389	$ 778
47%	123	116	$ 42	$ 334	$ 668
46%	118	111	$ 36	$ 289	$ 578
45%	114	105	$ 31	$ 251	$ 503
44%	109	100	$ 27	$ 220	$ 440
43%	105	95	$ 24	$ 193	$ 386
42%	100	89	$ 21	$ 170	$ 340
41%	95	84	$ 19	$ 150	$ 300
40%	91	79	$ 17	$ 132	$ 264
39%	86	74	$ 15	$ 116	$ 232
38%	82	68	$ 13	$ 102	$ 204
37%	77	63	$ 11	$ 89	$ 179
36%	73	58	$ 10	$ 78	$ 156
35%	68	53	$ 8	$ 68	$ 135
34%	64	47	$ 7	$ 58	$ 116
33%	59	42	$ 6	$ 50	$ 99
32%	55	37	$ 5	$ 42	$ 83
31%	50	32	$ 4	$ 34	$ 69
30%	45	26	$ 3	$ 28	$ 55
29%	41	21	$ 3	$ 21	$ 42
28%	36	16	$ 2	$ 15	$ 31
27%	32	11	$ 1	$ 10	$ 20
26%	27	5	$ 1	$ 5	$ 10

The equilibrium prices for producing a 42% chrome concentrate with the different price variables, when compared to table 8, start out lower but increase more with the higher feed material. Above 44% feed material, the equilibrium price is higher than in table 8. The equilibrium prices are lower, and the range of input material for above $0 only start at 26% as illustrated in figure 19. This is graphically represented in figure 19 with the higher input grade, the higher the equilibrium price, but less gradually than Scenario 2.

Figure 19: Equilibrium line if 44% concentrate has 5% more chrome in the tailings than the 20% chrome in tailings for the 42% concentrate as per table 9

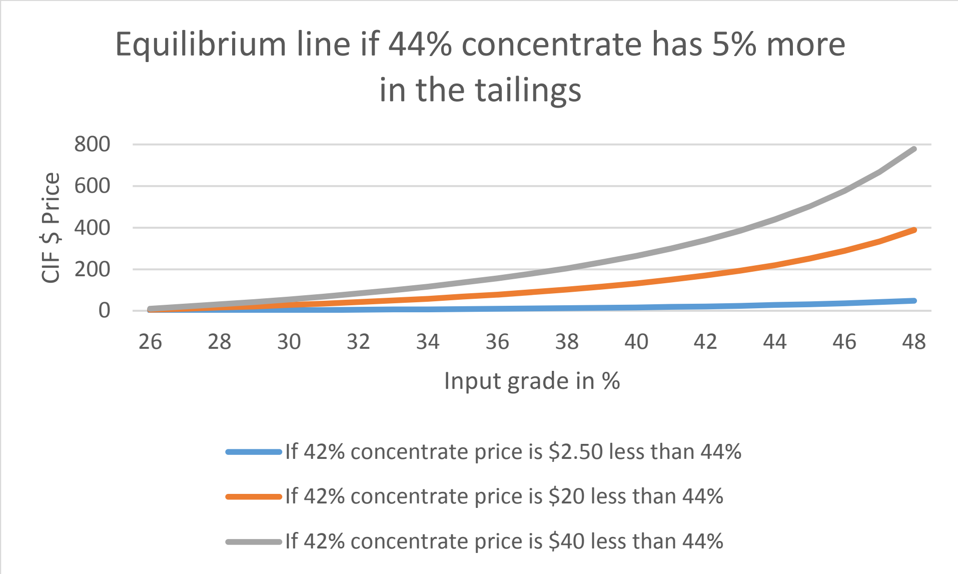
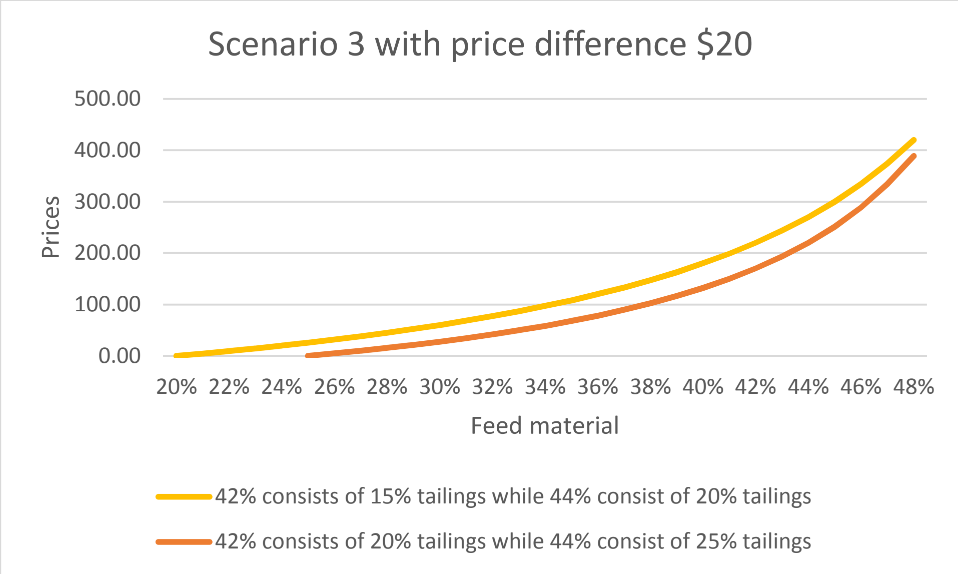


Figure 19 illustrates the different equilibrium lines for the different price variances when there is 20% chrome content in the tailings when producing a 42% chrome concentrate and 25% in the tailings when producing a 44% chrome concentrate. The higher the price variance, the higher is the equilibrium price for the different input grade. The equilibrium line for the $40 variance is at $200 when the input grade is at 38% while the equilibrium is at $100 when the price variance is $20. When the feed grade is 48% the difference in equilibrium line is very clear with the $40 price variance at $800 and the $20 price variance at $400. The price variance of $2.50 is a bit more difficult to read from figure 19 since the line stays below $100.

Figure 20 illustrates the difference between the two assumptions on the chrome content in the tailings with a difference of 5% and a price variance of $20. The line illustrates the equilibrium line for both assumptions. As can be seen on the figure, the price of $200 for 42% concentrate there is a 1% difference in input grade for equilibrium point for the two different assumptions on the tailings of 15% and 20% when producing a 42% chrome concentrate product.

Figure 20: Comparison in equilibrium lines when there is a 5% chrome difference in the tailings based on scenario 3



3.5 RESULTS AND DISCUSSION

Comparing the prices from January 2013 to October 2017, the average difference in the prices is USD 20 CIF. The prices' differences range from USD 40 to the lowest difference being USD 2.50. By using the model created with the different formulas, it was applied to the different scenarios to calculate the equilibrium for different market conditions.

In Scenario 1 when the tailings for both products was assumed to be the same, the input grade didn't matter because the equilibrium stayed at one price. The variance that did matter was the price variance between the different products. The higher the price difference, the higher the equilibrium line is. This applies to all three scenarios. The input grade is relevant for Scenario 2 and 3 when calculating the equilibrium. This is due to the difference in tailings when producing a 42% chrome concentrate and a 44% chrome concentrate. The more the chrome content increased in the tailings, the more the equilibrium line moved to higher input material required for the same equilibrium point and price. An increase in chrome content difference for tailings when producing two products also affected the equilibrium line. The line started horisontal when tailings was equal to each other but the more the difference increased, the more the line started to curve. This illustrated that with higher grade in input material the tailings difference in production have a more relevant effect on the model. The different scenarios address the different variables for input material and price for the case study. The next chapter will conclude on the model and suggest recommendations.

3.6 SUMMARY

Based on the model created by combining the mass recovery formula with the total sales and equilibrium formula it was possible to determine the turning point for different scenarios. The model was tested against different input grades and price for equilibrium was determined. The scenarios considered price difference of $2.50, $20 and $40 CIF as per historical price data collected. Different scenarios for tailings was also developed with a difference of 0%, 2% and 5% chrome content when producing the two different products. This scenarios was developed through assumptions based on the literature available.

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

4.1 INTRODUCTION

This study specifically focused on chrome with a broad outlook on the different markets it affects. An overview was done on steel, and stainless steel as this is the industries that are relevant to chrome. China and South Africa were identified as key role players in the industry and discussed in more detail. Mining in South Africa was reviewed while the study then focused on chrome ore and the development into concentrate. The formulas identified for the study was reviewed and scenarios for the case study was identified. The combination of the formulas created a model that can identify the most beneficial product to produce and this was applied to the case study with illustrations in table and figure formats.

4.2 ACHIEVEMENT OF THE OBJECTIVES OF THE STUDY

The primary objective of this study was to develop a model that could assist in calculating the most viable point of production. This point will be financially more beneficial to produce a chrome concentrate of 42% rather than a 44% depending on the sales price and input grade of the material. The equilibrium price, or for this study the turning point, is where the opportunity cost is less for 44% than for 42%. Then it is more beneficial to change from producing a 44% to a 42%. The opposite also applies. The achieved of the objective will be discussed in the following section.

4.2.1 Research objective 1: Conceptualise from the literature the steel and stainless-steel industry

The steel and stainless-steel industry was conceptualised during the literature study in chapter 2 by identifying the significance and growth of each industry. The different uses and the relevance towards chrome were also discussed.

4.2.2 Research objective 2: Conceptualise from the literature the Chinese and South Africa macro, as market indicators and end-users of chrome

China and South Africa as key role players in the chrome industry was conceptualised in the literature study.

4.2.3 Research objective 3: The study will conceptualise from literature mining in South Africa, especially chrome ore

The mining of chrome specifically in South Africa is an important objective of the study and was conceptualise by first discussing mining in South Africa and then directing more focus on the mining of chrome ore in the Bushveld Igneous Complex.

4.2.4 Research objective 4: Exploring chrome ore and discuss the beneficiation process and the relevance to the IDSR-concept

The necessity of chrome was discussed in chapter two by identifying the vital properties. The different types of processes were reviewed before the study focussed on the gravity separation process in the form of a spiral plant. The spiral was discussed in detail as it has the most relevance to the study and the IDSR-concept.

4.2.5 Research objective 5: Describing the mass recovery formula and the relevance to the model

The mass recovery formula was defined as the formula that can theoretically define the maximum efficiency of a spiral. The relevance to the model was discussed as the quantity aspect of revenue management.

4.2.6 Research objective 6: Describing the total sales formula and the relevance of pricing to the model.

The prices of the two different products are part of the main objective of the study and the total sales formula as well as the relevance of pricing to the model was described in the study.

4.2.7 Research objective 7: To create the model by combining different variable formulas

The equilibrium formula was defined as the final formula for the model in chapter 2 before the model was created in chapter 3. The model combined total sales with the recovery model. The equilibrium formula was added to define the outcome of the model.

4.2.8 Research objective 8: To test the model as a case study with different scenarios

The model was tested in a case study by applying three different scenarios that focus on tailings. The first scenario assumed that for both a 42% concentrate and 44% concentrate the tailings was the same. The second scenario applied the assumption that there were 2% more in the tailings when a 44% concentrate is produced while scenario 3 assumed a 5% difference. All three scenarios were studied with the assumption of 15% in the tailings of the 42% concentrate and 20% tailings of the 42% concentrate. The scenarios also considered the three price differences of $2.50, $20 ad $40.

4.2.9 Research objective 9: The pricing of chrome will be investigated

The difference in price for the last four years was discussed and included in a case study by applying the price variance to each scenario.

4.2.10 Research objective 10: Determining the effectiveness and necessity of the model by using historical data and illustrating it with different examples.

The conclusion for each scenario determined the effectiveness and the necessity of the model. This objective will be reached in the section when the conclusions of the study are discussed.

4.3 MAIN FINDINGS

The following model was developed and applied in the scenarios:

Model

$$M = (P(X) \times (X-t_1)/(f-t_1)) - (P(Y) \times (Y-t_2)/(f-t_2))$$

Where:

M= Model

P(X) = Price of 44% Concentrate

X =44%

P(Y) = Price of 42% Concentrate

Y=42%

f= Feed/ Input chrome %

t= tailings chrome content in percentage.

The study illustrated the effect of different feed material, tailings and price difference on the production of chrome. The following conclusions could be reached on each variable.

- For feed material, the conclusion can be made that the higher the grade of the material, the more likely it becomes that it is more beneficial to produce a 44%, depending on the price;
- For lower feed material it was illustrated that depending on the price it is more likely to be beneficial to produce a 42% concentrate;
- The bigger the price difference is between the two products, the higher the equilibrium is, meaning the more likely it will be that it is more beneficial to produce a 44% chrome concentrate; and
- The higher the difference in the tailings is, the more limited the feed material become and it becomes more likely that it will be financially more beneficial to produce a 42% concentrate since the equilibrium line moves away from the lower tonnages.

When this model is applied in practice, the variables of the plant will be known. This will make it easier to identify which product will be financially more beneficial to produce. Managers can easily apply this model to alleviate production decisions. This is illustrated in figure 21 that demonstrates the model in the form of an Excel sheet and how it can be applied to decision making in a real industry scenario:

Figure 21: Chrome price optimisation model

Plant variables:			Sale variables:	
Product 1: (X)		44%	Price of 44% concentrate: P(X):	$
Product 2: (Y)		42%		
			Price of 42% concentrate: P(X):	$
Feed grade (f):		%		
Tailings grade for product 1 (t_x):		%	Price difference:	$
Tailings grade for product 2 (t_y):		%		
Result by applying formula:			Positive= 44% concentrate	
$M=P(X)*(f-t_x)/(X-t_x) - P(Y)*(f-t_y)/(Y-t_y)$			Negative= 42% concentrate	

The blue blocks in figure 21 represent the plant variables that are required which can be monitored in practice. The yellow blocks represent prices. The result, after the variables is applied, provides the product most beneficial to produce.

By applying the model on the 31st of October 2017 price of $182.50 for 42% concentrate and $202.50 for 44% concentrate, the following conclusion can be made for the different scenarios:

- Scenario 1: Same percentage in tailings, it is more beneficial to produce a 44% concentrate.
- Scenario 2: With 2% more in the tailings, if tailings are 15% and input grade is higher than 36% it is more beneficial to produce a 44% concentrate, below 36% input material will be better utilised as 42% concentrate. If the tailings are 20%, the input material needs to be higher than 40% to be beneficial to produce a 44%.
- Scenario 3: With a 5% difference in the tailings it is more beneficial to produce a 42% unless the input material is higher than 40% chrome.

As illustrated, clear conclusions can be made from the data especially if more variables are known.

4.4 RELEVANCE

The model can be applied to any chrome gravity process plant even if it is designed on the concept of the spiral plant as ong as the variables are known. The model is a management tool and can be applied to practical cases to support decision making in the production process. The sales price of the chrome concentrate can also be the price offered at the site if the conditions of sale are the same for both products. Due to the silo-effect in most companies where different sections doesn’t communicate this tool is relevant to support marketing and production section in the company to be able to make the best CSR decision for the company.

4.5 RECOMMENDATIONS FOR CHROME PRODUCTION PLANT

From the data and application in the case study, it is evident that this model could be applied in the chrome industry by each production-plant to determine if they are producing the financially more beneficial product. The variables of the plant regarding feed material and tailings should be known when using the model by a plant manager. The prices are available for sales manager either by market research or published on different websites. As a manager of a chrome production plant with the previously mentioned variables known, the model can determine what is more financially beneficial to produce.

From the case study the following the recommendations can be made for chrome producers:

- If the feed grade that is used by a production plant is low, it is more beneficial for a production plant to produce a 42% chrome concentrate. This is dependent on the tailings from the spiral.
- If the spiral plant makes use of higher feed grade material, it is more likely to be more beneficial to produce a 44% chrome concentrate. Depending on the tailings the plant produces.
- The lower the chrome content in the tailings the spiral plant produce, the more likely it is that it is to be more beneficial to produce a 44% chrome concentrate. The higher the chrome in the tailings from the spiral plant, the more likely it is that it is more beneficial to produce a 42% chrome concentrate. Depending on the feed material of the plant.
- The management and monitoring of the difference in tailings when producing the two different products is important in determining when it is more beneficial to produce a 42% chrome concentrate or a 44% chrome concentrate. It is more beneficial if the difference is as small as possible. If this is not managed or controlled properly, the plant may end up producing the product that is financially less rewarding.
- The price difference between the two products is an important variable to monitor. The more the price difference increases the higher the equilibrium line and the more the probability increase that it is more beneficial to produce a 44% concentrate. If it is not monitored, the outcome of the model regarding which product should be produced may lead to the incorrect decision.
- The model is based on what theoretically can be recovered from the spiral when applied in the actual environment, it is recommended that the mass recovery accuracy is tested in a plant and the variance to the theoretical mass recovery be determined. The mass recovery can then be adjusted accordingly in the model for a more accurate plant-specific outcome.

- By implementing the chrome price optimisation model, chrome producers can assure that they are producing the correct product to optimise profits

4.6 LIMITATIONS AND CHALLENGES

This study is limited by assuming that the results are based on theoretical tonnages and the fixed percentage outcome chrome concentrate products of 42% and 44%. Another assumption is that the chrome in the waste material is set at a fixed percentage. Practical cases will show that this varies due to inconsistencies that can occur in a plant. These limitations, however, do not affect the model but rather the results that the model will provide.

Because of the different variables, the challenge was to illustrate the effect properly while including a lot of variables that will be known when the model is used for its design in practise. Another challenge was the literature study on mass recovery as the formula is often used in literature but limited literature is available on the subject .

4.7 SUGGESTIONS FOR FUTURE STUDIES

One of the risks of further beneficiation of chrome is Cr(VI), but this only becomes a risk when chrome concentrates is exposed to smelting process (Geldenhuis & Horne, 2002:661). Cr(VI) contaminates water and is known as one of the chemicals posing the greatest threat to humans (Basu *et al.*, 2015:159). Further study should be done on this and the relevance to the model.

The change in suppliers reacting to the market can affect other markets since the next user of chrome can reach a supply issue of oversupply on one product and undersupply for the next. Further study should be done on the next user, and the effect a lower grade chrome will have in the process. Further investigation into the model could be done by adding other variables to support the outcome more.

One of the risks to the mining industry is illegal mining. Illegal mining is currently a big problem in South Africa as it is a difficult issue to address with the high unemployment rate. Workers would rather stay underground and risk death than risk the chance to be arrested (Nhlengetwa & Hein, 2015:2-3). Workers that participate in illegal mining is creating income for their families and other members of the community, which contributes to the economy (Thornton, 2014). The question then becomes: do they contribute more good than the damage they cause? When arrested approximately 70% are illegal immigrants which costs the stakeholders R6 billion in annual value (ChamberOfMines, 2017:32). Further study should be done on the impact of illegal mining in the chrome industry and the affect it has on market prices.

Unions in South Africa with a strong membership support, like COSATU (Congress of South African Trade Unions), have the power to enforce the changes they want for instance demanding a change at the presidential level (de Villiers *et al.*, 2014:53). When unions decide to go on strike in the mining industry, it has a highly negative effect, not only on the loss of production and salary but also on the loss of investment and investor confidence in the country (Bohlmann *et al.*, 2015:403). The lack of confidence goes both ways since the unions are under the perception that the mining companies are not willing to share their wealth (Lane *et al.*, 2015:471), not just being socially responsible but doing more to uplift the poor communities. One thing mining companies have learned is that the power of the unions should not be ignored (Ting, 2016:68). These stakeholders have a huge influence on the mining industry and consultation should be done with all stakeholders before, during and after mining and they need to be taken seriously (Leonard & Lebogang, 2017:6). Further study should be done on affect Unions have on plant operations.

4.8 CONCLUSION

This study developed a model that can assist how managers in the chrome industry react to the price changes in the chrome concentrate market. The importance was indicated in the literature review when the different industries where chrome is used were discussed. Steel and specifically stainless steel is products that are part of our daily lives. It is consumables, and the industry continues to grow as the world develops. South Africa and China are the two market indicators and end-users of chrome. China is one of the biggest importers of chrome ore and chrome concentrate while South Africa is the biggest exporters who can be expected from a mineral-rich country. Chrome ore beneficiated processes were discussed, and the spiral plant was identified as the focus area for the study. It is based on a gravitation process that makes use of water. The efficiency of a spiral is very important for the model. The cutter in a spiral determines the product that will be produced. Managers should monitor the position of the cutter and make sure the spiral is efficient.

Three formulas were identified for the creation of the model namely mass recovery, total sales and equilibrium. The combination of the three formulas created the model that can determine when it is financially more beneficial to produce a 42% chrome concentrate or when it is financially more beneficial to produce a 44% chrome concentrate. Factors from the plant that influence the decision are the chrome in the feed material and the chrome in the tailings material. These are the factors that can be internally managed. The external factor that also influences the decision is the market price of the two products is the price. This may be difficult to manage, but by monitoring the price and applying the model, the product that is financially more beneficial can be produced.

For the case study, three scenarios were identified. The first scenario assumed that the tailings would be the same when producing a 42% concentrate and a 44% concentrate. Equilibrium prices were identified for the three different price variances. For this scenario, it was identified that the input material grade didn't affect the equilibrium price. The percentage of the tailings was an important factor.

Scenario two assumed that there were 2% more in the tailings when producing a 44% concentrate while scenario three assumed 5% more in the tailings when producing a 44% concentrate. For these scenarios, the chrome in the input material influences the outcome of the equilibrium point. The lower grade tended to indicate it is more beneficial to produce a 42% chrome concentrate while the higher grade tended to indicate towards producing a 44% chrome concentrate. These two scenarios also illustrated that it is more beneficial to produce lower tailings. The application of the model on the case study provided the areas where it is more beneficial to produce a 42% concentrate, but when applying the model in practice it provides a clear answer if it is beneficial to produce a 42% concentrate with the only assumption that the plant is managed according to information used in the model.

LIST OF REFERENCES

Arık, E. & Mutlu, E. 2014. Chinese steel market in the post-futures period. *Resources Policy*, 42 (Supplement C) :10-17.

Baddoo, N.R. 2008. Stainless steel in construction: A review of research, applications, challenges and opportunities. *Journal of Constructional Steel Research*, 64 (11) :1199-1206.

Bascur, O.A. & Linares, R. 2006. Grade recovery optimization using data unification and real time gross error detection. *Minerals Engineering*, 19 (6) :696-702.

Basu, A., Panda, S. & Dhal, N. 2015. Potential Microbial Diversity in Chromium Mining Areas: A. *Bull. Env. Pharmacol. Life Sci*, 4:158-169.

Baxter, R. 2017. Mining Charter draft concerns. *Inside Mining*, 10 (1) :32-33.

Beukes, J.P., du Preez, S.P., van Zyl, P.G., Paktunc, D., Fabritius, T., Päätalo, M. & Cramer, M. 2017. Review of Cr (VI) environmental practices in the chromite mining and smelting industry – Relevance to development of the Ring of Fire, Canada. *Journal of Cleaner Production*, 165 (Supplement C) :874-889.

Bhandary, A.K., Gupta, P., Mukherjee, S., Chaudhuri, M.G. & Dey, R. 2016. Beneficiation of Low Grade Chromite Ore and Its Characterization for the Formation of Magnesia-Chromite Refractory by Economically Viable Process. *World Academy of Science, Engineering and Technology, International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering*, 10 (8) :1096-1104.

Blitz, A. 2017. Lessons from the steel industry: if you can't compete on price, innovate your way to value-added differentiation. *Strategy & Leadership*, 45 (5) :26-32.

Bohlmann, H.R., Van Heerden, J.H., Dixon, P. & Rimmer, M. 2015. The impact of the 2014 platinum mining strike in South Africa: An economy-wide analysis. *Economic Modelling*, 51:403-411.

Bouffard, S.C. 2015. Benefits of process control systems in mineral processing grinding circuits. *Minerals Engineering*, 79 (Supplement C) :139-142.

Carter, C. 2017. How to Calculate Sales Revenue in Accounting. http://smallbusiness.chron.com/calculate-sales-revenue-accounting-18906.html Date of access: 13 Nov 2017.

Castro, P.M., Sun, L. & Harjunkoski, I. 2013. Resource‐task network formulations for industrial demand side management of a steel plant. *Industrial & Engineering Chemistry Research*, 52 (36) :13046-13058.

ChamberOfMines. 2017. MINE SA 2016: FACTS AND FIGURES. www.Chamberofmines.org.za.

Cho, H. & Kong, M.-k. 2017. The Steel Industry over the Next Two Decades. *Asian Steel Watch*, 3:38-45.

Cramer, L.A., Basson, J.**, amp & Nelson, L.R. 2004. The impact of platinum production from UG2 ore on ferrochrome production in South Africa. *Journal of the Southern African Institute of Mining and Metallurgy*, 104 (9) :517-527.

Cronin, C. 2014. Using case study research as a rigorous form of inquiry. *Nurse Researcher (2014+)* , 21 (5) :19.

Cyril, O., Oo, A., A, D. & N, A. 2017. The Steel Industry: A Stimulus to National Development. Vol. 06.

Das, S. 2015. Quantitative mineralogical characterization of chrome ore beneficiation plant tailing and its beneficiated products. *International Journal of Minerals, Metallurgy, and Materials*, 4 (22) :335-345.

de Villiers, C., Low, M. & Samkin, G. 2014. The institutionalisation of mining company sustainability disclosures. *Journal of Cleaner Production*, 84 (Supplement C) :51-58.

Dixit, P., Tiwari, R., Mukherjee, A.K. & Banerjee, P.K. 2015. Application of response surface methodology for modeling and optimization of spiral separator for processing of iron ore slime. *Powder Technology*, 275 (Supplement C) :105-112.

Edwards, D.P., Sloan, S., Weng, L., Dirks, P., Sayer, J. & Laurance, W.F. 2014. Mining and the African Environment. *Conservation Letters*, 7 (3) :302-311.

Erdiaw-Kwasie, M.O. & Alam, K. 2017. Corporate minerals and community development dilemma in the Surat Resource Region, Australia: Implications for resource development planning. *Environmental Science & Policy*, 77 (Supplement C) :122-129.

Farjadi, M. & Azari, J. 2004. Effect of chrome ore quality on ferrochrome production efficiency. (*In*. Proceedings: Tenth International Ferroalloys Congress organised by. p. 4) .

FerroAlloyNet. 2017. 2013-2017 Chrome Industry Data Analysis Report. http://www.ferroalloynet.com/report/20132017__chrome__industry__data__analysis__report.html Date of access: 01/11/2017 2017.

Firoz, A. 2014. Long Term Perspectives for Indian Steel Industry. *Ministry of Steel, Economic Research Unit mimeo, New Delhi, May*.

Flyvbjerg, B. 2006. Five misunderstandings about case-study research. *Qualitative inquiry*, 12 (2) :219-245.

Geldenhuis, J.M.A.K. & Horne, A.W. 2002. Recovery of valuables and stabilization of chrome (VI) in stainless steel flue dust fines. (*In*. 85th Steelmaking Conference proceedings organised by Steelmaking Division of The, I. & Steel, S., Nashville, TN. p. 661-668) .

Grewal, I. 2016. Introduction to Mineral Processing. http://met-solvelabs.com/library/articles/mineral-processing-introduction Date of access: FEBRUARY 2016.

Grossman, M. 2017. Two visions, one collaboration? Part of a future for US - China relations. *The Asia-Pacific Journal*, 15 (2-2) :1-6.
Hadera, H., Harjunkoski, I., Sand, G., Grossmann, I.E. & Engell, S. 2015. Optimization of steel production scheduling with complex time-sensitive electricity cost. *Computers & Chemical Engineering*, 76:117-136.
Hamann, R. & Kapelus, P. 2004. Corporate social responsibility in mining in Southern Africa: Fair accountability or just greenwash? *Development*, 47 (3) :85-92.
Honaker, R., Jain, M., Parekh, B. & Saracoglu, M. 2007. Ultrafine coal cleaning using spiral concentrators. *Minerals Engineering*, 20 (14) :1315-1319.
Horne, R. 2017. Patterns of empowerment and disempowerment in the South African mining sector. *African Review of Economics and Finance*, 9 (1) :1.
ISSF. 2017. ISSF STAINLESS STEEL IN FIGURES 2017. worldstainless.org.
Ito, S. & Fujimaki, R. 2017. Optimization beyond prediction: Prescriptive price optimization. (*In*. Proceedings of the 23rd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining organised by: ACM. p. 1833-1841) .
Jujur, I.N., Sah, J., Bakri, A. & Wargadipura, A.H.S. 2015. ANALYSIS OF OXIDE INCLUSIONS ON MEDICAL GRADE 316L STAINLESS STEEL USING LOCAL RAW. *INTERNATIONAL JOURNAL OF TECHNOLOGY*, 6 (7) :1184-1190.
Keil, M. & Ndou, E.D. 2016. Human Resources Strategy and Change: Intervention on Leadership Development at the Department of Energy in South Africa. *Handbook of Human Resources Management*:1285.
Kuramochi, T. 2017. Assessment of CO2 emissions pathways for the Japanese iron and steel industry towards 2030 with consideration of process capacities and operational constraints to flexibly adapt to a range of production levels. *Journal of Cleaner Production*, 147 (Supplement C) :668-680.
Lane, A., Guzek, J. & Van Antwerpen, W. 2015. Tough choices facing the South African mining industry. *Journal of the Southern African Institute of Mining and Metallurgy*, 115 (6) :471-479.
Lee, K. & Ki, J.-h. 2017. Rise of latecomers and catch-up cycles in the world steel industry. *Research Policy*, 46 (2) :365-375.
Leonard, L. & Lebogang, T. 2017. Exploring the Impacts of Mining on Tourism Growth and Local Sustainability: The Case of Mapungubwe Heritage Site, Limpopo, South Africa. *Sustainable Development*.
Li, C., Ripley, E.M., Sarkar, A., Shin, D. & Maier, W.D. 2005. Origin of phlogopite-orthopyroxene inclusions in chromites from the Merensky Reef of the Bushveld Complex, South Africa. *Contributions to Mineralogy and Petrology*, 150 (1) :119-130.

Long, Y., Pan, J., Farooq, S. & Boer, H. 2016. A sustainability assessment system for Chinese iron and steel firms. *Journal of Cleaner Production*, 125 (Supplement C) :133-144.
Ma, S.-h., Wen, Z.-g., Chen, J.-n. & Wen, Z.-c. 2014. Mode of circular economy in China's iron and steel industry: a case study in Wu'an city. *Journal of Cleaner Production*, 64 (Supplement C) :505-512.
MacNeil, J.A.L. & Dimitrakopoulos, R.G. 2017. A stochastic optimization formulation for the transition from open pit to underground mining. *Optimization and Engineering*, 18 (3) :793-813.
Michaud, D. 2013. Metallurgical accounting formulas. https://www.911metallurgist.com/blog/metallurgical-accounting-formulas Date of access: 29 July 2016.
Miller, P. 2017. SA mining at risk of missing out on benefits of global commodities uptick. *Journal of the Southern African Institute of Mining and Metallurgy*, 117 (1) :vi-vi.
Mishra, B.K. & Tripathy, A. 2010. A preliminary study of particle separation in spiral concentrators using DEM. *International Journal of Mineral Processing*, 94 (3) :192-195.
Murthy, Y.R., Tripathy, S.K. & Kumar, C.R. 2011. Chrome ore beneficiation challenges & opportunities - A review. *Minerals Engineering*, 24 (5) :375-380.
Nhlengetwa, K. & Hein, K.A.A. 2015. Zama-Zama mining in the Durban Deep/Roodepoort area of Johannesburg, South Africa: An invasive or alternative livelihood? *The Extractive Industries and Society*, 2 (1) :1-3.
Oberthür, T., Junge, M., Rudashevsky, N., de Meyer, E. & Gutter, P. 2016. Platinum-group minerals in the LG and MG chromitites of the eastern Bushveld Complex, South Africa. *Mineralium Deposita*, 51 (1) :71-87.
Ottosson, M. & Kindström, D. 2016. Exploring proactive niche market strategies in the steel industry: Activities and implications. *Industrial Marketing Management*, 55 (Supplement C) :119-130.
Oxford. 2017. Equilibrium. https://en.oxforddictionaries.com/definition/equilibrium Date of access: 27 November 2017.
Pan, X. 2013. Effect of South Africa chrome ores on ferrochrome production. (*In* organised by: International Conference on Mining, Mineral Processing and Metallurgical Engineering.
Panda, L., Banerjee, P.K., Biswal, S.K., Venugopal, R. & Mandre, N.R. 2014. Modelling and optimization of process parameters for beneficiation of ultrafine chromite particles by selective flocculation. *Separation and Purification Technology*, 132 (Supplement C) :666-673.
Petrie, J. 2007. New Models of Sustainability for the Resources Sector: A Focus on Minerals and Metals. *Process Safety and Environmental Protection*, 85 (1) :88-98.

Popescu, G.H., Nica, E., Ştefănescu-Mihăilă, R.-O. & Lăzăroiu, G. 2016. The United States (US) Steel import crisis and the global production overcapacity till 2016. *Metalurgija*, 55 (3) :538-540.

Rasmussen, M.B. & Lund, C. 2018. Reconfiguring Frontier Spaces: The territorialization of resource control. *World Development*, 101 (Supplement C) :388-399.

ReportBuyer. 2017. Mining of Chrome and Production of Ferrochrome. https://www.prnewswire.com/news-releases/mining-of-chrome-and-production-of-ferrochrome-in-south-africa-2016-300396136.html# Date of access: 31/10/2017 2017.

Richards, J. 2006. "Precious" metals: The case for treating metals as irreplaceable. *Journal of Cleaner Production*, 14 (3) :324-333.

Rossi, B. 2014. Discussion on the use of stainless steel in constructions in view of sustainability. *Thin-Walled Structures*, 83:182-189.

Runeson, P. & Höst, M. 2008. Guidelines for conducting and reporting case study research in software engineering. *Empirical Software Engineering*, 14 (2) :131.

Stoffberg, M. 2017. Plant pictures.

Sun, W., Dong, K. & Zhao, T. 2017. Market demand dynamic induced mechanism in China's steel industry. *Resources Policy*, 51 (Supplement C) :13-21.

Swaine, M.D. 2015. Chinese views and commentary on the "One Belt, One Road" initiative. *China Leadership Monitor*, 47 (2) :3.

Thornton, R. 2014. Zamazama, "illegal" artisanal miners, misrepresented by the South African Press and Government. *The Extractive Industries and Society*, 1 (2) :127-129.

Ting, M. 2016. Historical Review of the Relationship between Energy, Mining and the South African Economy. *EARTH, WIND AND FIRE*:60.

Tripathy, S.K. & Rama Murthy, Y. 2012. Modeling and optimization of spiral concentrator for separation of ultrafine chromite. *Powder Technology*, 221 (Supplement C) :387-394.

Uberman, R. 2014. Valuation of Mineral Resources in Selected Financial and Accounting Systems. *Natural Resources*, 5 (09) :496.

Vela-Almeida, D., Brooks, G. & Kosoy, N. 2015. Setting the limits to extraction: A biophysical approach to mining activities. *Ecological Economics*, 119:189-196.

Wang, P., Wolf, S.A., Lassoie, J.P., Poe, G.L., Morreale, S.J., Su, X. & Dong, S. 2016. Promise and reality of market-based environmental policy in China: Empirical analyses of the ecological restoration program on the Qinghai-Tibetan Plateau. *Global Environmental Change*, 39:35-44.

Warren, P. 2014. A review of demand-side management policy in the UK. *Renewable and Sustainable Energy Reviews*, 29:941-951.

Wills, B.A. & Finch, J. 2015. Wills' mineral processing technology: an introduction to the practical aspects of ore treatment and mineral recovery: Butterworth-Heinemann.

Wübbeke, J. & Heroth, T. 2014. Challenges and political solutions for steel recycling in China. *Resources, Conservation and Recycling*, 87（Supplement C）:1-7.
Xiaowei Pan, D. 2013. Effect of South Africa Reductants on Ferrochrome Production. *IFAC Proceedings Volumes*, 46（16）:352-358.
Yuldashev, F. & Sahin, B. 2016. The political economy of mineral resource use: The case of Kyrgyzstan. *Resources Policy*, 49（Supplement C）:266-272.
Zainal, Z. 2017. Case study as a research method. *Jurnal Kemanusiaan*, 5（1）.

APPENDIX 1: LANGUAGE LETTER

Dynamic Language &
Translation Specialists

Antoinette Bisschoff
71 Esselen Street, Potchefstroom
Tel: 018 293 3046
Cell: 082 878 5183
antoinettebisschoff@mweb.co.za
CC No: 1995/017794/23

Monday, 18 December 2017

To whom it may concern,

Re: **Letter of confirmation of language editing**

The dissertation **Evaluating the price of different grades of chrome ore in South Africa by M. Stoffberg (21628025)** was language edited. The referencing and sources were checked as per NWU referencing guidelines. Final corrections remain the responsibility of the author.

Antoinette Bisschoff

Officially approved language editor of the NWU since 1998
Member of SA Translators Institute (no. 100181)

Precision ... to the last letter