Cut-off Grade Optimisation for a Bimetallic Deposit: A Case Study of the Ruashi Mine Copper-Cobalt Deposit

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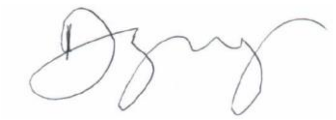
Johannesburg, 2017

DECLARATION

I declare that this research report is my own unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any other degree or examination in any other University.



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ABSTRACT

The research was driven by the need to optimise the Ruashi Mining operation to prevent further high-grading without destroying the value of the mine. Ruashi Mining incurred a five-year stripping backlog caused by the drive to reduce costs. As a result of this, a decline in metal production was imminent in the subsequent years. The study was conducted mainly using SimSched Direct Block Scheduler (SimSched DBS) in comparison with schedules from Datamine Net Present Value Scheduler (NPVS) and MineSched. The scenarios investigated have shown that running a mine based on break-even cut-off grade does not optimise the net present value of an operation as shown through the results of Ruashi Mining. The research also proved that royalty affects the cut-off grade for Ruashi Mining, and cannot be ignored.

The proper scheduling of wasting stripping resulting from cut-off grade optimisation has contributed to a timeous exposure of high grade to avert the decline in metal production. All the three scenarios have shown that high grade ore can be availed on time, thus producing a smooth metal output for the life of mine.

Cut-off grade optimisation is very crucial for any mining organisation as it is the main driver of value. Ore reserves are important in the determination of a company's share price. High cut-off grade results in fewer reserves, and vice versa. Since mineral reserves are the source of revenue, therefore, the higher the reserves, the higher the revenue. Low cut-off grade may result in the processing of material that does not give high profit at the beginning of the life of mine. This, therefore, lowers the mining company's net present value. This makes it imperative to optimise the cut-off grade during the mine life in order to optimise the net present value.

During mining operations, there are various stakeholders whose interests must be considered during cut-off grade optimisation because they derive many benefits from the mine. These stakeholders include shareholders, employees, government, the community and non-governmental organisations.

Cut-off grade optimisation has shown that there is an opportunity to improve the net present value of Ruashi Mining. SimSched gives a higher net present value (NPV) compared to the current Ruashi life of mine schedule. This indicates that SimSched can be used to improve the NPV for Ruashi by producing an optimised schedule. It is important to note though that there is need for the software to have provisions to take into account the initial stockpile status so that there is a holistic approach to the schedule optimisation.

The grade-tonnage curve is steeper closer to zero implying that a small change in cut-off grade has a huge impact on reserves. Based on the results of the study it was clear that optimisation in SimSched DBS results in a steeply declining cut-off grade policy compared to NPVS. In addition, optimisation in SimSched leads to highly accelerated mining rate and massive stockpiling.

Royalty is a cost which has to be incorporated in cut-off grade optimisation. The study has shown that the cut-off grade for Ruashi is increased by 19.8%. Ignoring royalty may result in overvaluing of an operation. Environmental considerations favour the optimisation of the use of the mieral resources. Consideration of environmental costs lowered the cut-off grade for Ruashi by 16%.

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DEDICATION

I dedicate this document to my beloved wife, Nyadzie Blessing for the unconditional support, love, and patience while I spent long nights and days studying. I also dedicate it to my loving children, Tafadzwa, Tinayeshe, Tawananyasha Faith and Tavonga Lemuel for being good children while I was busy with this research. Lastly but not least, I dedicate it to my brother Enock who made me into what I am today. If he was alive, he would be rejoicing to see the fruits of his work and love.

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LIST OF ABBREVIATIONS

%TCu - percent Total Copper

%TCo – percent Total Cobalt

BOMZ – Black Ore Mineralised Zone

CSV – Comma Separated Value

DRC – Democratic Republic of Congo

GAC – Gangue Acid Consumption

NPV – Net Present Value

NPVS – Net Present Value Scheduler

SAMREC – The South African Code for Reporting of Exploration Results, Mineral Resources and Mineral Reserves

SimSched DBS – SimSched Direct Block Scheduler

USA – United States of America

SNEL - Société Nationale de Electricité

CHAPTER 1: INTRODUCTION

1.1 Chapter overview

This chapter defines the problem to be investigated and the justification for the research. It also suggests reasons for the current situation of Ruashi Mining as well as the importance of cut-off grade optimisation to the mining industry in general. Further, it points out some of the main contributors to cut-off grade optimisation and the need for cut-off grade optimisation.

1.2 Problem Statement

The main challenges which prompted this research can be stated as:

- The stripping backlog incurred in the past which is destroying the value of Ruashi Mining;
- Unavailability of high grade ore due to previous high-grading which threatens the premature closure of the mine. This can be mitigated by cut-off grade optimisation;
- The opportunity to improve the Net Present Value (NPV) of Ruashi Mining in cognisance of the prevailing operational challenges.

Ruashi orebody hosts two economic minerals, namely cobalt and copper. Copper is the main product while cobalt is a by-product. The life of Ruashi Mining is currently based on the external cut-off grade calculated during pit optimisation. This external cut-off grade is used to generate ore classes in the block model in preparation for scheduling in MineSched software. The ore classes are shown in Table 1.1 below. The classes used were generated for blending purposes only.

The grade is based on two components, namely acid soluble and insoluble parts. It is necessary to determine the acid soluble part because it is the one which is leachable. The lower limit value for low grade ore is the break-even cut-off grade calculated during pit optimisation. The coded block model is used in MineSched for life of mine scheduling. Sensitivities of different target mill feed grades are used to generate different scenarios subsequent to which the scenario that generates the best cash flow is chosen for budgeting purposes. This has resulted in high grading and a waste stripping backlog. In fact, whenever there was a need to reduce mining costs the reduction was always achieved by reducing waste stripping. This high-grading, compounded by the reduced stripping has resulted in a decline in metal production in the second year of the life of mine plan. This has to be addressed through accelerated waste stripping in the initial two years of the life of mine as shown in Figure 1.1 generated from MineSched.

Table 1.1: Material classification for Scheduling

Grade Range	**Description**	**Destination**
0 - 0.30% TCu	Waste	Waste dump
0.30 - 0.90%TCu	Mineralised waste	Mineralised waste dump
0.90 – 2.50%TCu	Low Grade Ore	Run of Mine Pad/Low Grade Stockpile
2.50 – 3.50%TCu	Medium Grade Ore	Run of Mine Pad/Medium Grade Stockpile
Above 3.50%TCu	High Grade Ore	Run of Mine Pad/High Grade Stockpile
Above 0.20%TCo and below 0.90%TCu	Cobalt Ore (BOMZ)	Run of Mine Pad

Where:

%TCu is % Total Copper grade

%TCo is % Total Cobalt grade

BOMZ is Black Ore Mineralised Zone, which is cobalt ore.

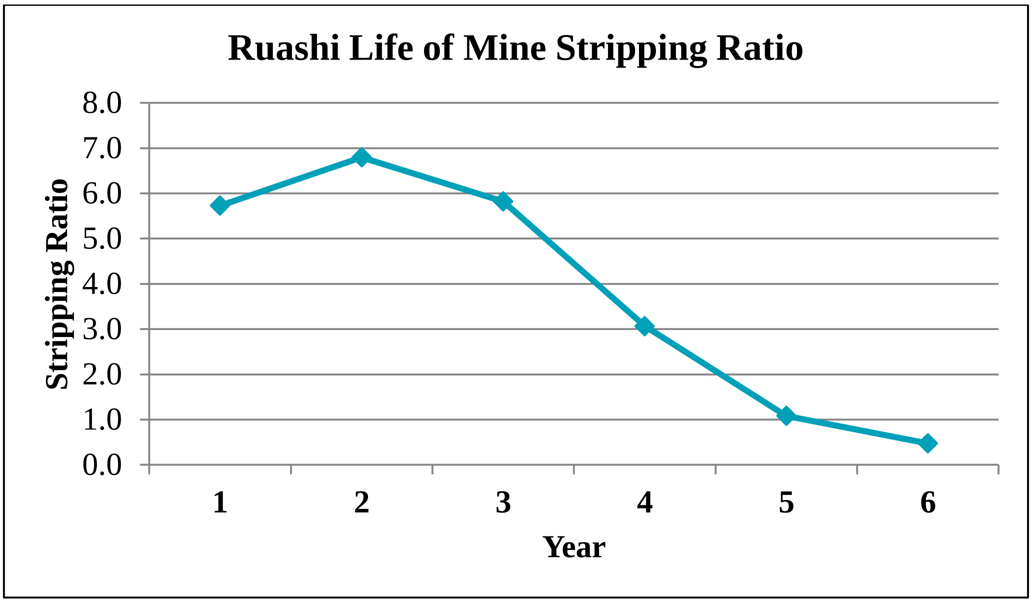


Figure 1.1: Variation of Ruashi life of mine stripping ratios

Accelerated stripping is not favoured by the time value of money concept because higher cash outflows must be delayed as much as possible. In the case of Ruashi, accelerated waste stripping has to be done to rectify the waste stripping backlog incurred in the last four years. Although ideally waste stripping would have been spread evenly in the first four years to improve the NPV, there has not been flexibility to do so.

The stripping backlog is reflected in the decline in life of mine feed grades in Figure 1.2 as generated from the MineSched life of mine schedule. The feed grade drops in the second and third years because not enough high grade ore is exposed by that time. The cobalt grade is high in the first two years because of the exposure of the enriched cobalt cap in the Pit 3 pushback.

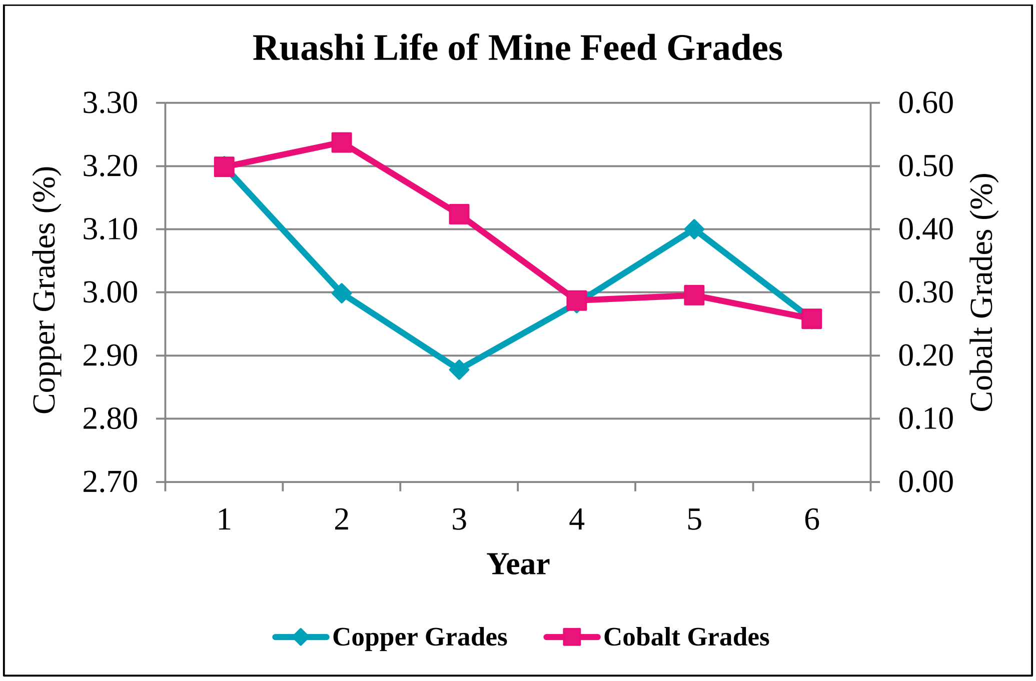


Figure 1.2: Variation of Ruashi life of mine feed grades

It is the aim of this research to investigate the possibility of optimising the feed grades so as to optimise the NPV of the mine in order to mitigate the effects of the waste stripping backlog. The mining schedule produced from the cut-off grade optimisation is used to direct the mining operations. The periodic pit shells generated during scheduling are used in short term planning. This ensures that the planned grade is achieved while accelerating the stripping also, hence metal production is not drastically affected. As stated before, the cut-off grade generated through pit optimisation is referred to as an external cut-off grade. The external cut-off grade is applied during pit optimisation to identify blocks that generate revenue. Blocks below the external cut-off grade are treated as waste. Once the pit optimisation is done and a design is produced, post-pit optimisation is carried out to optimise the life of mine extraction strategy of the resource within the designed pit. There are different value drivers that can be optimised to maximise the value of the mine. These include internal cut-off grade and increasing throughput (Breed & van Heerden, 2016). The internal cut-off grade refers to the cut-off grade applied to material inside the designed pit and is used to determine the destination of blocks within the pit which must be mined as ore or waste (Baird &

Satchwell, 2001). This report is aimed at producing an optimised internal cut-off grade policy for Ruashi using the SimSched Direct Block Scheduler (DBS) software developed by MiningMath.

1.3 Background

Hall (2014) defines grade as any parameter that is used to describe the relative value of a block of rock. The grade can be the metal grade in a single metal deposit, or a metal equivalent grade or a monetary value measure in a polymetallic deposit. Cut-off grade represents the minimum amount of valuable product that a measured quantity of rock must contain for it to be considered as ore (Rendu, 2008). Cut-off grade is used to distinguish between ore and waste. This cut-off grade is normally the break-even cut-off grade that is calculated during pit optimisation to determine the ultimate pit. Once the pit shape has been determined, and the operational pit is designed the internal cut-off grade is subsequently applied to material inside the designed pit. Cut-off grade optimisation is applied to the internal cut-off grade which is used for scheduling material for processing or stockpiling. There are different types of internal cut-off grades depending on the objective and parameters used in their calculation. The bottlenecks in the production system also determine the type of cut-off grade applied. The bottleneck at Ruashi Mining is the mill capacity, but mining capacity is unlimited under the present operating conditions. The maximum mill throughput is 1.25 million tonnes but the mine can produce in excess of 2.5 million tonnes of ore. So if the mill throughput were to be doubled the mine can still meet the mill feed requirements (Lane, 1988).

Mining is a business and businesses are undertaken to make profit and to grow wealth for shareholders. One significantly important value driver in all mining operations is the cut-off grade. Ultimately cut-off grade policy adopted by a mining operation determines its profitability and life. According to Hall (2014), the cut-off policy is a planned sequence of cut-offs for an operation over time. There is a correlation between a high cut-off grade policy and increase in short-term profitability and NPV of the mine. However, increasing the cut-off grade results in a decrease in the life of the mine. Conversely, a high cut-off grade policy may be implemented to reduce political risk by getting higher financial return over a short time period. It is rare for the cut-off grade to remain the same over the life of the mine even if costs and product prices remain unchanged. Commodity prices are cyclic, meaning that they go through repetitive periods of high prices followed by those of low prices. A shorter mine life might reduce time-dependent opportunities offered by price cycles. For example, copper prices are very low at present (year 2016) but are expected to increase again in the next three to four years which coincides with the time of the end of life for Ruashi mine. Governments and local communities expect long-term benefits from mining operations; hence a short life of mine can give rise to high socio-economic impact due to reduced long-term employment and decreased benefits to employees and local communities (Rendu, 2008).

Optimal cut-off grades depend on limiting capacities in the various stages of the production process (Lane, 1988). In the case of Ruashi Mining, there has been a drive to minimise stockpiling of low grade ore. The grade distribution of the orebody dictates that a lot of low grade ore be mined in order to expose higher grade ore. It is the objective of this report to derive an operating strategy that maximises the profit of the mine by also optimising stockpiling. This may also extend the life of the Ruashi mining operations. This profit maximisation is based on stockpiling low grade material during the earlier years of the life of mine through prioritising the processing of high grade ore to generate higher cash flow in earlier years (Nieto & Bascetin, 2006).

The optimised cut-off grade is used in the simulation of mine processes to determine which configuration yields the maximum economic value (Gholamnejad, 2008). Given varied purposes of cut-off grade, it is important to define strategic goals at the outset before commencing the cut-off grade optimisation.

Ruashi Mining has gone through a period of high- grading and reduced waste stripping. This has resulted in decreased metal production and increased costs due to the need to accelerate waste stripping in order to clear the stripping backlog to avail higher grade ore. There is a need to run a post pit optimisation to produce an optimised cut-off grade policy for the future development of Ruashi so as to maximise the value of the mine.

This cut-off grade policy is also expected to produce a more manageable waste stripping schedule that will help address the waste stripping backlog.

1.4 Justification for cut-off grade optimisation at Ruashi Mining

The research seeks to address key operational challenges at Ruashi Mining. The major areas addressed in the research are:

- to mitigate the effects of high-grading that has been practised in previous years;
- to address the stripping backlog caused by previous drives to reduce costs by deferring waste stripping without adverse impacts on profits;
- to investigate the opportunity to improve the NPV of Ruashi Mining.

The ultimate goal of the mining business is to extract valuable minerals. The value of a block of material is normally expressed as a grade. The revenue obtainable from the extraction of the mineral from that block is linked to the grade. There is a minimum grade below which the mining operation runs at a loss.

In any production process of a mining venture, there are bottlenecks which result in opportunity costs. Processing low grade material in a production process that has bottlenecks result in lower metal production. Lower metal production results in lower revenue. This gives a loss in an opportunity for the company. Running an operation at break-even cut-off grade destroys value. Given that the time value of money favours higher cash inflows in the early years of the life of mine to optimise net present value (NPV) it is prudent to determine a cut-off grade policy that takes this into account. The cut-off grade that maximises the NPV of an operation in the presence of bottlenecks is of much higher value than the break-even cut-off grade. In the case of Ruashi, the mill is the bottleneck.

This report seeks to optimise the internal cut-off grade for Ruashi Mining and provide guidance on the scheduling process currently applied at the mine. Optimised cut-off grade policy aims to augment the life of mine planning process. The optimised cut-off grade policy provides the annual feed grades and pit mining progression in line with the required waste stripping to avail the ore. It is therefore the aim of this cut-off grade optimisation study to guide the operation on an optimised cut-off grade policy to address the stripping backlog. Continued high-grading is not sustainable in the medium to long term as it may lead to the sterilisation of resources. Hence it can make economic sense to operate under an optimised cut-off grade policy.

1.5 Present status of cut-off grade policy

Storrar (1977) refers to cut-off grade as 'pay limit' which he defines as the minimum value at which ore can be mined and treated without profit or loss. This definition is however based on break-even analysis which takes into account financial parameters only. Under the break-even, analysis prices are compared with costs after being adjusted to account for metallurgical recovery. Under this analysis, if the grade of the mineralised material is sufficient for the revenue obtained to pay for the costs associated with extracting, processing and selling, it is classified as ore. This break-even cut-off grade calculation model does not account for grade distribution of the mineralisation and neither does it account for the capacities of the mining and processing plants. The break-even model can be used as long as it is augmented by the outcomes of more comprehensive models, like those recommended by Lane (Hall, 2014).

Mortimer (1950), cited in Hall (2014) considered both the financial aspect on one hand and the geology and nature of the mineralisation expressed by the tonnage versus grade curves on the other. This dual holistic consideration ensures the satisfaction of break-even conditions and the delivery of specified profit targets by the delineated material. Lane's (1988) approach accounts for financial, geological as well as production systems capacities to handle rock, ore and product. Cut-off grades are determined based on which process in the system is a bottleneck. Lane also introduced the concept of opportunity costs if lower grade ore displaces higher grade ore in the feed. This opportunity cost is included in cut-off grade optimisation. This is re-visited in Section 2.15. Parametric grades, especially when dealing with polymetallic deposits, are indirectly related to the grade distribution of the mineralised body. This enables the calculation of equivalent grades for polymetallic ore bodies in order to simplify cut-off grade optimisation. Section 2.6 explains the most commonly used parametric cut-off grades. The need for stockpiling arises from the fact that an optimum cut-off grade policy entails a general decline in cut-off grades during the life of the mine. Material with grades that are not economic to treat in the earlier years may have economic benefits in later years of the life of mine. Hence no material originally classified as ore is discarded as waste (Lane, 1988).

Rendu (2008) elaborates on Lane's work and simplifies the complex mathematical derivations from Lane's approach. For Rendu, capital costs incurred before the calculation of cut-off grade are considered as sunk costs. Stay-in-business capital costs are to be recovered from the profits of the operation; hence they are included in cut-off grade calculation. Rendu elaborates on costs to be considered in cut-off grade calculation. The costs used determine whether the result is break-even, marginal, budget or planning cut-off grade (Rendu, 2008).

At Ruashi Mining, the marginal cut-off grade has been used to generate an optimum pit during pit optimisation (van Daalen, 2012). The marginal cut-off grade is similar to the processing cut-off grade. The selected optimal pit is subsequently used to design an operational pit. Various cut-off grades are defined in the Ruashi Mining Planning Protocol and they include planning, budget and marginal cut-off grades. The formulae for calculating these grades are given in Appendix A. The marginal cut-off grade is used to determine the processing cut-off grade whilst the price, costs and metal recoveries are used to determine the copper equivalent cut-off grade. This equivalent grade is subsequently built into the block model as an attribute. The copper equivalent cut-off grade is used for determining the resources and reserves based on the respective parameters which include prices and costs.

1.6 Data source, acquisition and treatment of the findings

This is a case study of the cut-off grade optimisation at Ruashi Mining. Ruashi Mining's 2016 budget forecast data and long term prices have been used in this study. Basing the study on Ruashi Mining's 2013 pit designs, various data sources were used for the research, including commodity prices, geotechnical, mining and metallurgical parameters. The commodity prices used are those supplied by Metorex Mineral Resources Management. Geotechnical, mining and metallurgical parameters were obtained from Ruashi Strategic Planning Assumptions and the block model used is called ruashi_jul_2014_v3.mdl that was last updated in July 2014. The May 2016 survey month-end topography has been used to deplete the model. The resulting periodic grades are used to produce a life of mine schedule.

1.7 Chapter 1 Summary

The problem to be addressed by this research report is to mitigate the effects of the high-grading previously practised at Ruashi Mining. This is achieved by generating an optimised cut-off grade policy for the mine. The distinction between external and internal cut-off grades is that the former is applied during pit optimisation to determine the optimum pit whilst the latter is for scheduling. It has however been shown in this chapter that this distinction is somewhat vague at many mining operations including Ruashi Mining. Optimisation of the internal cut-off grade prevents high-grading, especially when this is done simultaneously using software like SimSched DBS. High-grading has been practised at Ruashi Mining for the past four years and this has resulted in the need for accelerated waste stripping to maintain the target feed grade and throughput, and hence the metal output. Ultimately, cut-off grade optimisation is aimed at addressing this in a way that does not significantly impact on the NPV and cash flow for the mine. Benefits for implementing internal cut-off grade optimisation have been given in the chapter. The cut-off grade policy currently being practised at Ruashi Mining has also been explored and it needs improvement in many areas.

1.8 Structure of the report

Chapter 1 provides background to the study through outlining the nature of the problem to be addressed and giving the causes of the problem at Ruashi Mining. The chapter also justifies the need to address the problem promptly. Chapter 2 reviews some of the literature on cut-off grade and related parameters from ample literature on cut-off grade and other related economic factors. The methodology for the research is explained in Chapter 3. Results from three software are used in the research, namely SimSched DBS, Net Present Value Scheduler (NPVS) and MineSched. In addition, the preparation of the required inputs is described. Chapter 4 gives an overview of the Ruashi Mining operations focussing on location, geology, mining and processing. The chapter aims to provide an understanding of the context of Ruashi Mining operations. The results obtained from break-even analysis; NPVS and SimSched are presented in Chapter 5. The results from the scenarios are presented. Sensitivity and risk analyses are carried out in Chapter 6. Risk analysis is conducted using the trial version of @Risk software developed by Palisade Corporation. Chapter 7 rounds up the report by drawing conclusions from the research findings and ultimately provides recommendations for both Ruashi Mining and MiningMath who are the developers of SimSched DBS.

CHAPTER 2: LITERATURE REVIEW

2.1 Chapter Overview

Since Lane's 1988 work, the subject of cut-off grade calculation and optimisation has received a lot of scholarly attention. A lot of perspectives and knowledge have been added on the cut-off grade policy space. This chapter critically looks at the definition of cut-off grade as given by various authors. There is a general agreement on the definition of cut-off grade by most prominent authors like Rendu and Hall, and they also agree with Lane (1988). The section on cut-off grade dilemma shows that a lot more needs to go into the determination of the cut-off grade given the difficulty of attempting to balance the divergent interests of various stakeholders on a mining operation. The research also explains the different types of cut-off grade to clarify their usage and provides a brief discussion on costs used in cut-off grade determination. It is important to be able to know which costs apply at any particular point particularly given that some deposits host more than one economic mineral which should also be considered in the determination of cut-off grade. Notably, this study is based on a bi-metallic deposit which necessitates the need to discuss how it is handled in practice. Further, environmental considerations are important in cut-off grade estimation, with conservationists requiring the maximisation of the usage of the mineral resources and therefore slowdown in the opening of new mines (Rashidinjad, Osanloo, & Rezai, 2009). Mining companies are subjected to royalties and taxes on their produce and on mining claims. This is discussed in the section on royalty and taxes. The section on capacity constraints discusses the bottlenecks that may be present in the system. These bottlenecks give rise to different ways of deriving cut-off grades. The section on cut-off grade optimisation discusses ways of optimising NPV through cut-off grade optimisation in the context of mining revenues being affected by volatile commodity prices. This discussion leads to the topic on risk, given that mining is largely a risky business with long payback periods.

2.2 What is cut-off grade?

2.2.1 Distinction of mined material

It is important to understand all the parameters involved in deriving cut-off grades. There is a general assumption by many authors that all readers have the same understanding of mining terminology. The life of a mine begins with exploration in which a lot of money is spent. This investment in exploration must be recovered from the minerals that are later produced (Sinclair & Blackwell, 2004). Agricola, as way back as 1556, cited in Appleyard et al (2001), described the process of establishing a mine when he noted:

> "The miner ignorant and unskilled in the art digs out the ore without careful discrimination while the learned and experienced miner first assays and proves it, and when he finds the veins either too narrow and hard or too wide and soft, he infers therefrom that these cannot be mined profitably and so works only the approved ones" (Appleyard, Gilfillan, & Northcote, 2001).

This indicates that exploration has been recognised as a vital component of mining since time immemorial. Consequently, many steps are involved in coming up with the cut-off grade, and hence the reserves of a project. Many minerals are found in the crust in varying concentrations, and yet in many cases, the concentrations of the minerals are too low for economic extraction. Mining as an industry deals with the progressive concentration of minerals to a form where they become marketable. There is a boundary which distinguishes mineralised material that is extracted for further treatment from that which is discarded. This boundary is derived from a cut-off grade. The word 'ore' is used to describe the mineralised material which is extracted for treatment. Further, the establishment of the economic basis for determining cut-off grades also results in the economic definition of ore (Lane, 1988).

Hall (2014) defines grade as the ratio of the amount of product to the amount of ore in which it is contained. There is need to distinguish between three types of material, namely rock, ore, and product. The term rock refers to the total material that is mined before it has been separated into ore or waste. It also refers to all the material mined and transported from the pit. Ore represents the material that is destined for processing. The product is the valuable material that is extracted from the ore. Hall (2014) gives the following equation in order to clarify the classification of material in an open pit mine:

Rock = ore (treated or stockpiled) + waste = total material moved

It is also important to note that these materials are the major cost drivers for cut-off grade derivation and optimisation (Hall, 2014). The South African Code for reporting of exploration results, mineral resources and mineral reserves (SAMREC Code, 2009) describes a mineralised body as a resource only if there are reasonable prospects of eventual economic extraction. The term ore is reserved for that part of the resource that can be extracted economically at a defined point in time.

2.2.2 Grade and cut-off grade

Hall (2014) defines the term grade as a parameter that describes the relative value of a block of rock in the mineralised body. The grade may be expressed as:

- Grams per tonne (g/tonne) for gold or as a percentage (%) for base metals;
- Metal equivalent grade per tonne for multi-mineral deposits;
- Dollar value per tonne especially for multi-mineral deposits.

Relatedly, Asad and Topal (2011) define ore as the economically exploitable portion of a mineral deposit. Lane (1988) laid the foundation when he stated that cut-off grade is the boundary that distinguishes between material that is treated from that which is discarded. The cut-off grade represents the minimum amount of valuable product a given mass of material must contain for it to be classified as ore. It determines the profitability and the life of a mine. A high cut-off grade increases the short-term profitability of a mine and maximizes the NPV. However, high cut-off grades also shorten the life of the mine. In many cases, high cut-off grades are implemented where there is high political risk and investors aim to achieve high financial return over a short time to reduce exposure to risk (Rendu, 2008). It must also be pointed out that implementing high cut-off grades results in high stripping ratios and hence high unit costs due to handling the same material for reduced ore tonnages (John, 1985). It is also crucial to note that the cut-off grade is site specific because it is driven by unique characteristics inherent in that operation (Sinding & Larsen, 1995). Ultimately, cut-off grades vary with the geological characteristics of the material being mined.

Dagdelen (2001) adds to the definition of cut-off grade by noting that it is the grade that is used to distinguish between ore and waste during scheduling. He brings in the scheduling part which is silent in many definitions by the other authors. Most open pit mines are designed and scheduled using break-even analysis which maximises the undiscounted profits. The cut-off grade that maximises the NPV of the cash flows also depends on mining, milling, and refinery capacity limitations as well as the grade distribution within the deposit.

According to Crone and Hunter (1992), "the present value of a projected mining operation calculated at the nominated interest rate (a rate which reflects the cost of capital) gives a measure of the profitability of the mining operation. Therefore, maximization of present value represents a fundamental objective in guiding the conduct of a mining operation. Maximization of the present value means that the capital invested in the operation is being used most efficiently" (Crone & Hunter, 1992, p. 81). The cut-off grade is therefore that grade which determines whether mineralised material is processed, stockpiled or discarded. The present value of an operation can be improved by proper cut-off grade selection. A common approach is to determine the balancing situation, that is where the marginal grade of ore is such that the revenue obtained from its treatment balances the cost of producing the ore. Such an approach maximises the recovery of valuable minerals and maximises the (undiscounted) net revenue or profit. However, it is unlikely to maximize the NPV because if there is a large volume of material just equal to the cut-off grade treated early in the life of the operation, the treatment plant tends to be filled with material which yields low profit, with negative effects on the present value of the total operation (Crone & Hunter, 1992). Fundamentally, cut-off grade is the most important driver of value for a mining operation and therefore its implementation must be transparent and well understood by all stakeholders.

It is important to distinguish between the cut-off grade applied for the definition of ore and that used for deciding whether to process or not. Many mining operations use the same cut-off grade for both determining the ultimate pit and deciding whether to process or to discard a certain tonnage of material. The two processes are different and therefore the derivation of cut-off grades will also be different. Large, supergene-enriched porphyry copper deposits tend to have grade-tonnage curves that are relatively flat over the low grade range because they contain large tonnages of enriched copper ore and the proportion of the total ore tonnes that fall in the low grade range is relatively small. In porphyry deposits where supergene enrichment has been less well developed (as shown in Figures 24 and 25 for Ruashi Mining), grade-tonnage curves tend to be steeper and significant proportions of the total ore tonnage may fall in the low grade range. In the latter case, the resource contained inside the optimized pit limits can be sensitive to the cut-off value used and can be sensitive to where and when the cut-off is applied. The contained resource is sensitive to the assumptions made about metal prices, recoveries, costs and potential penalties associated with mining, processing, smelting and refining of concentrates (Baird & Satchwell, 2001).

Ore reserves, mine life and cut-off grades cannot be predicted with confidence because of volatile commodity prices and high costs prevalent in the mining industry. The prevailing conditions in the base metals industry dictate an improved understanding of the terms ore and cut-off grade and their proper application in mining strategic plans. The definition of ore or ore reserves is a dynamic concept, reflecting the cumulative effect of changes in geological, technical and economic conditions. The cut-off grade is determined to classify mineral resources as economic or uneconomic in a specified time frame. The author agrees with Pasieka and Sotirow (1985) when they state that the capacity of an existing operation is normally considered an imposed constraint for long-term planning purposes rather than a basis for further option analysis to optimise the plan (Pasieka & Sotirow, 1985).

Noble (1993) defines the cut-off grade as that grade above which mineralised material is economic to mine and process. Material below the cut-off grade is discarded as waste, but material above may be classified as ore under the right conditions. Noble's definition separates the mineralised material into three parts, namely material below the cut-off grade (waste), material equal to the cut-off grade (not classified) and material above the cut-off grade (ore). It is essential to determine what happens to the material with grade equal to the cut-off grade. Should it be treated as ore or waste? Hall (2014) asserts that the tonnage of material whose grade is equal to the cut-off grade is mostly insignificant for practical purposes. He however suggests that the material whose grade is equal to the cut-off grade be classified as waste since it does not generate any profit for the operation. However, what is regarded as waste in the short term may become economic to process in the long-term. Hence, a cut-off grade optimisation policy is applicable at a point in time.

Up till the present times, the cut-off grade has been applied to the main product in the mineralised material. Situations may arise where some impurities result in penalties to the operation. Consumers of the by-product cobalt concentrates from Ruashi impose penalties if the lead and iron content in the concentrates exceed specified quantities. Gangue acid consuming (GAC) elements must be minimised in the ore that is fed to the leach tanks to minimise acid consumption.

The financial viability of every mining project rests with a proper definition of the economic portion of a mineral deposit. The economic definition of ore dictates that at the very least every increment of mineralized material has to contain a sufficient concentration of metals enough to pay for the cost of mining, processing, and all the related costs of access.

Where there is limited mill capacity, the use of the break-even cut-off grade in scheduling ore processing results in a lower NPV for the operation. The focus on NPV maximisation gives rise to cut-off grades which are higher than the break-even cut-off grade in the earlier years of the life of mine. This results in declining cut-off grade strategy. The opportunity costs determine how high the implemented cut-off grade is from the break-even cut-off grade (Dagdelen & Mohammed, 1997). The declining cut-off grade strategy is important because some of the overhead costs tend to decrease especially for an operation which is in a harvesting mode and is nearing closure like Ruashi. Lower grade material can then be treated during this time of reduced fixed costs. In most mining operations higher grade material tends to get depleted first, resulting in excess capacity which can then be used for treating low-grade material from the stockpiles (if any).

Dagdelen (2001) divided the cut-off grade optimisation process into the stages shown in Figure 2.1. The initial production capacity in mining is estimated based on costs and commodity prices. The production costs, in this case, all the costs including head office are used to produce the ultimate pit. Cut-off grade estimation is a part of the whole pit optimisation and design process. Pit optimisation is an iterative process as shown in Figure 2.1. Economic block values are used to determine whether the block value can pay for the removal of overburden above it. The break-even cut-off grade is used for this analysis (Gholamnejad, 2008). The chosen ultimate pit is used to design pushbacks. The internal cut-off grade is applied for material in the pushbacks for use in production scheduling.

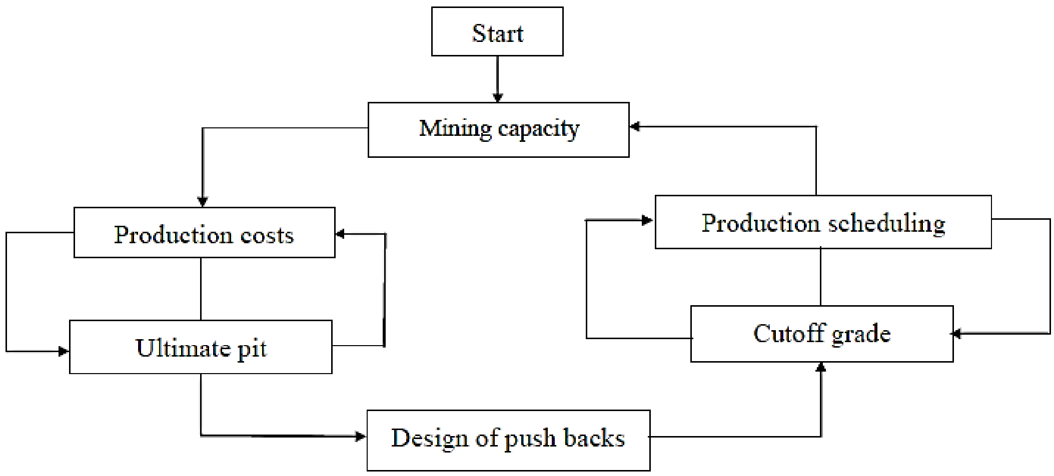


Figure 2.1: Open pit long-term production planning variables interacting in a circular fashion (Dagdelen, 2001)

2.3 The cut-off grade dilemma

There are different stakeholders for any mining operation who may have diverging interests from those of the operating policies of an operation (Sinding & Larsen, 1995). In other words, a mining operation's policies have wider repercussions on various stakeholders which renders the calculation of cut-off grade somewhat complex. It becomes a challenge to be able to satisfy all the stakeholders, more so in these days where there is emphasis on the importance of the Social License to Operate (SLO).

Mining companies no longer have the liberty to conduct business on their terms. A mine may fail to start operating regardless of all the necessary approvals having been acquired if the community does not consent to it operating. The SLO is not merely a piece of paper but consent, though unwritten, by the community for the mining to go ahead. This SLO can be withdrawn at any time if the community is infuriated by the operation. Many mining operations are operating in volatile communities, especially in the Democratic Republic of Congo (Macfarlane, 2014).

According to Sinding and Larsen (1995), mine employees may adopt lower than optimal cut-off grades in order to prolong the life of the mine for longer term employment. Where managers' bonuses are tied to the reserves declared, this may result in sub-optimal cut-off grades being applied in order for the managers to earn their bonuses. The various stakeholders influencing the determination of cut-off grade are shown in Figure 2.2. The parent company is concerned with overall financial performance of the group. However, debt service, share performance on the stock market or internal finance needs may dictate a different cut-off grade policy with higher cash inflows at the beginning of the life of mine (Sinding & Larsen, 1995). The recent sharp decline in commodity prices has resulted in impaired assets for many mining companies. A number of them have also declared the impairment of their assets around the world. This has also dealt a serious blow to share prices on the stock market.

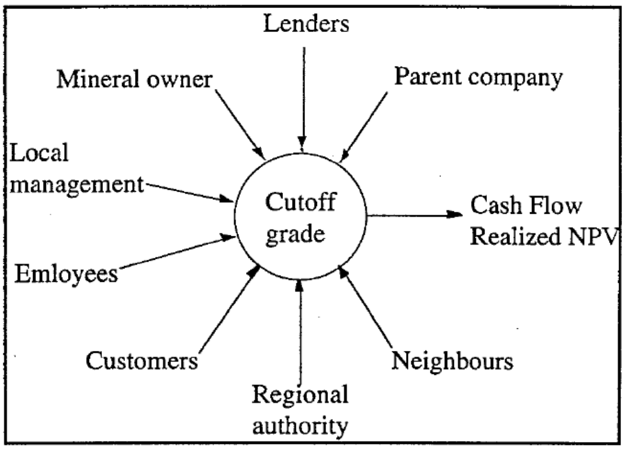


Figure 2.2: Stakeholders in the cut-off grade determination (Sinding & Larsen, 1995)

A high cut-off grade enhances short-term profitability and maximises the NPV of a project, which is beneficial to shareholders and other financial stakeholders, including government and local communities. Conversely, a shorter mine life may result in lower longterm socio-economic benefits due to reduced long-term employment and decreased benefits to employees and local communities. Banks and other financial institutions may also impose their requirements in the way in which cut-off grades are determined. In some instances, a conscious decision might be made to increase the mining capacity while keeping the processing capacity constant. This allows an increase in cut-off grade. Some of the lower-grade material may be stockpiled for processing at a later date. In turn stockpiling may increase the life of the processing facilities but may also result in increased environmental risks and decreased metallurgical recovery of stockpiled material. Sulphide ores tend to cause acid drainage which is detrimental to the environment. Some ores tend to oxidise when exposed to the environment and hence their recovery is also affected. Reserves enter into the calculation of capital depreciation, company book value, unit cost of production and taxes. Published reserves are also linked to the value that the financial markets give to a mining company (Prasetya & Simatupang, 2012).

Reserves are published to inform stakeholders for informed decision making. It is important to understand the interests and objectives of all stakeholders and take them into consideration in cut-off grade determination (Rendu, 2008). Figure 2.3 shows the complex interrelationships among stakeholders in the determination of cut-off grades.

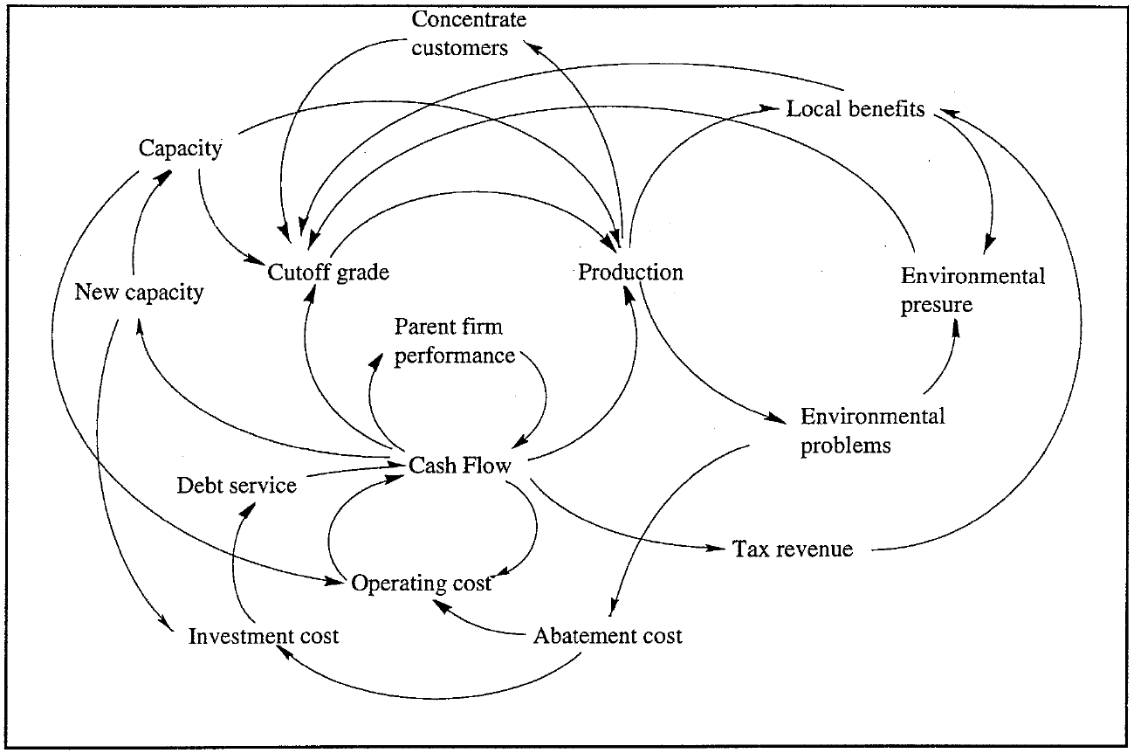


Figure 2.3: Interrelationships of factors influencing cut-off grade policy (Sinding & Larsen, 1995)

Lenders are more concerned about debt service and less about optimal cut-offs. They are most interested in stable cash flows over the repayment period. The mineral owner lays claim to part of the mineral rent derived from the operation by raising tax revenues. The rents are based on various tax instruments most of which are based on profits, calculated net rent or revenue. Government receives the largest discounted revenues if an optimal cut-off policy is pursued at a mining operation. Tax may also be based on actual mineral output or fixed annual payments. In such cases a cut-off grade policy which maximises the life of mine is preferred. Even if it is both optimal and rational to favour an optimal cut-off grade policy, it may serve to exacerbate economic cycles in the local economy. An optimal cut-off grade tends to concentrate cash flows in a much shorter period, and tax revenues are correspondingly concentrated. This gives large but short-lived revenue streams to the regional authority. Since the authority is likely to be politically unable to resist pressure to spend the revenue this gives rise to corresponding bursts in government spending. This creates two problems in the regional economy. First, boom and bust cycles associated with the concentrated exploitation of mines under optimal cut-off grade policies are exacerbated by high levels of government spending. Second, once government expenditures have increased, they are much more difficult to reduce when incomes decline (Sinding & Larsen, 1995).

Sinding and Larsen (1995) assert that adoption of suboptimal cut-off grades by local management is only likely when the managers have a reasonable expectation of extending their employment beyond the closure date indicated by an optimal policy. If the turnover rate for local management is such that management is replaced over a period shorter than the remaining life, then only the last manager has a real incentive to extend mine life. Employees derive benefits from production in the form of local benefits and have an interest to extend the mine life to continue enjoying these benefits including guaranteed long term employment.

The extent of environmental disturbance depends on both how long the mining operations go on and how extensive they are. An optimal cut-off grade policy results in a shorter and more concentrated mining operation followed by closure. The amount of ore mined is lower, and as a result, the quantity of waste generated is also smaller. While local environmental concerns favour optimal cut-off grade policies, and local employment favours maximisation of mine life through lower cut-off grades, another environmental consideration favours lower than optimal cut-off grade policies. By extracting more material from each mine, fewer sites will have to be disturbed to produce the same quantity of metal (Sinding & Larsen, 1995).

2.4 Types of cut-off grade

There has been confusion in the choice of cut-off grade to apply. Baird and Satchwell (2001) clarify this point, arguing that the break-even cut-off grade, where NPV of the whole project is equal to zero, is used for getting optimum pit shell or stope shape in underground mining. Once the pit size or stope shape has been determined, a different set of cut-off grades then applies. Hence, for open pit mining, there are two classes of cut-off grades; external and internal cut-off grade. External cut-off grade is applied during pit optimisation to define the ultimate pit. Internal cut-off grade is applied after pit optimisation for blocks that are in the optimal pit to define ore reserves. This is the point where the delineation of ore and waste is done (Baird & Satchwell, 2001).

Pasieka and Sotirow (1985) explain the application of different cut-off grades by means of a diagram as shown in Figure 2.4. They show which cut-off grades are applied for strategic planning and which ones are for operational planning. It is critical to note that ore-waste delineation is only applied for operational purposes depending on the short range objectives. On the other hand, strategic planning mainly addresses the overall life of mine project value and long term objectives. It is, therefore, important to understand which part of the planning cycle is being undertaken in order to apply the correct cut-off grade.

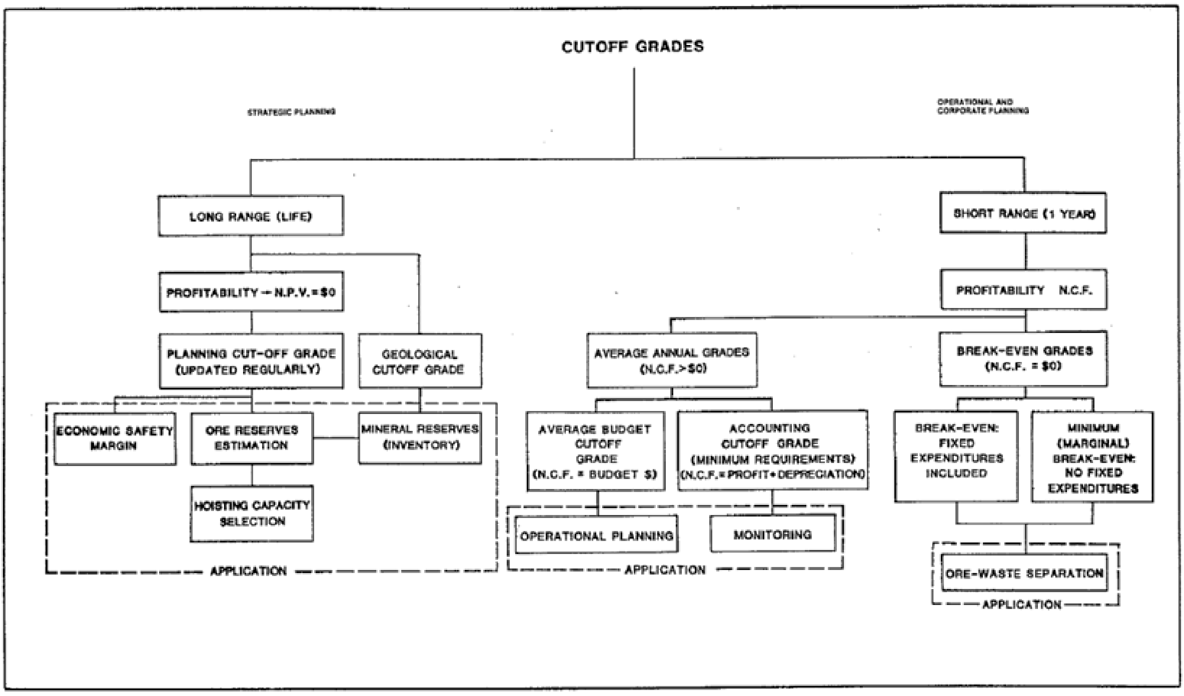


Figure 2.4: Definition/purpose of cut-off grades (Pasieka & Sotirow, 1985)

Where:

N.P.V = net present value

N.C.F = net cash flow

The formulae used in the calculation of different types of cut-off grade are given in Appendix A.

2.4.1 Geological cut-off grade

This is used for generating grade frequency distributions in order to separate mineralised material from waste and plot grade-tonnage curves for the mineralised material. The geological cut-off grade is used to estimate ore resources. The ore resources are part of the mineralised material which show reasonable prospects of eventual economic extraction (Pasieka & Sotirow, 1985).

2.4.2 Planning cut-off grade

As stated by Pasieka and Sotirow (1985), the planning cut-off grade is used for strategic planning. This is the grade at which the NPV of the project is equal to zero. The project must be able to cover capital, operating and financial costs. The project must also be able to cover all taxes and royalties during its life. The planning cut-off grade is also used for determining the mine capacity or plant capacity.

2.4.3 Budget cut-off grade

This reflects the cut-off grade that is required in order to generate some required cash flow in a particular year. This is normally required in order to satisfy a particular corporate objective for a desired cash flow for the company (Pasieka & Sotirow, 1985).

2.4.4 Accounting cut-off grade

According to Williams (2014), the accounting cut-off grade is the annual cut-off grade which is sufficient for a specified capacity to deliver revenue that covers operating cost, depreciation of fixed assets and minimum profit requirements. Pasieka and Sotirow (1985) pointed out that depreciation is a noncash cost and hence its use may have a negative effect on the operational cut-off grade strategy.

2.4.5 Break-even cut-off grade

This is the grade whose revenue covers all out-of-pocket cash expenses. These costs include fixed and variable costs, corporate and mining taxes and all allocated capital expenditures (Pasieka & Sotirow, 1985). Dagdelen and Kawahata (2007) define the economic break-even cut-off grade as that grade which can be used to differentiate between ore and waste and is determined by equating the value at the mill to the value at the dump. For no additional dumping cost this grade is derived as follows:

$Value_{mill}$ (\$/ton) = (P – s) * g * y – m – c

$Value_{dump}$ = - m

Where

P: price

s: sales and refining costs

g: grade of the material

y: recovery

m: mining cost

c: process cost

and at the breakeven cut-off grade,

$(P – s) * g_{breakeven} * y – m – c = - m$

Therefore

$g_{breakeven} = c/((P – s) * y)$

To operate the mill with full capacities, yearly ore tonnes (Q_c), stripping ratio (SR), the determination of the yearly mining capacity (Q_m) and the yearly metal production (Q_r) are presented as follows:

$Q_m = Q_c \times (SR + 1)$

Yearly profits are then calculated as follows (Dagdelen & Kawahata, 2007):

$Profits = (P – s) \times Q_r – Q_c \times c – Q_m \times m$

The break-even analysis is used to determine the final pit limits. The break-even point is that point in the life of a mine where the operating costs are equal to the value of the product sold.

2.4.6 Minimum (marginal) cut-off grade

The marginal cut-off grade is that which meets only the variable operating costs (excludes allocated administrative and other fixed operating and capital costs). It is used to determine the lowest grade which could be mined without losses if there is no other mineralised material available for the specified capacity to generate a positive net cash flow (Pasieka & Sotirow, 1985). This grade is used to separate ore from waste within the optimum pit limit.

2.5 Costs used in cut-off Grade calculation

Operating costs are those costs incurred in the execution of a mining operation. Some costs are incurred to move the total rock, ore or the product produced. It is important to classify and correctly allocate costs in order to accurately derive cut-off grades. It is also important to identify the behaviour of costs with respect to rock, ore and product. Costs must be allocated according to the physical parameters that drive them. These parameters are referred to as cost drivers (Hall, 2014). Musingwini (2011) in Tholana (2012) define operating costs as money which is spent in a process in order to produce a product. Operating costs are categorised according to their behaviour as the underlying level of activity changes. The activity level refers to production volume (Tholana, 2012).

Operating costs are divided into fixed and variable. Fixed costs are expenses that do not change in proportion to the level of activity within a specified time. Such costs are normally given as dollars per year or per month. Each elapsed period results in the expenditure of the stated amount regardless of the quantity of production. Variable costs change in direct proportion to the level of production. The higher the quantity produced, the higher the cost incurred. Table 2.1 gives examples of fixed and variable costs. The profit from the operation is determined by the difference between the revenue realised and the operating costs incurred. The profit is the difference between the total costs and the revenue as shown in Figure 2.5 (Tholana, 2012). The break-even volume is that volume where revenue received balances out the total costs incurred. All production volumes above the break-even volume will generate profit. If the operating costs are higher than the revenue, the operation incurs a loss as shown in Figure 2.5. All volumes below the break-even volume will generate a loss for the operation. The break-even point forms the basis for the derivation of the break-even cut-off grade for the operation (Birch, 2016).

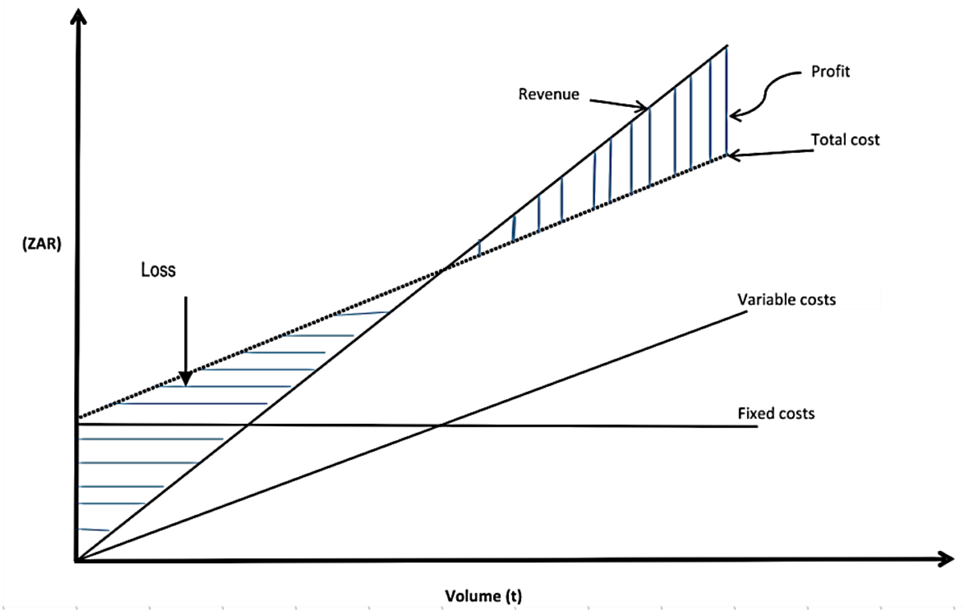


Figure 2.5: Cost-volume relationships (Tholana, 2012)

Table 2.1: Operating cost categories

Examples of fixed costs	Examples of variable costs
• Wages and salaries • Administration • Pumping • Interest expenses • Depreciation • Business licenses • Insurance • Permit fees	• Drilling • Blasting • Sampling • Loading • Flotation • Smelting and refining • Crushing and grinding the ore • shipping

Pasieka and Sotirow (1985) show that operating costs are classified into direct and indirect mining, milling, smelting, refining and marketing costs. Taxes and royalties payable in cash are treated as cost items. Capital expenditures include expenses incurred for exploration, permanent development, new and replacement equipment and capitalised supplies which are necessary to start and/or maintain production. All capital expenditures incurred prior to the time (year) of cut-off grade determination should be treated as sunk costs. If previously incurred capital expenditures are included into the cut-off grade calculations, the resulting cut-off grade will be higher, resulting in lower reserves declared. On the other hand, higher cut-off grade may result in the operation being uneconomic due to fewer reserves hence loss of capital already spent.

According to Birch (2014), costs which are included in the cut-off grade calculation vary throughout the life of an operation. A budget cut-off grade is used in the earlier years of the project to enable the initial capital to be recovered. The budget cut-off grade is calculated by considering the costs plus an additional percentage for capital recovery (Birch, 2016). In the final years of the life of mine, costs are minimal as a result of less stripping or development costs, resulting in areas that were previously marginal becoming profitable. At this stage the marginal cut-off grade can be used (Lane, 1988).

2.6 Cut-off grades for polymetallic deposits

Rendu (2008) defines polymetallic deposits as mineral occurrences that contain more than one metal of economic value. Calculation of cut-off grades must consider the contribution of each of the metals to the total revenue. There are however some elements which may cause penalties for the operation. These penalties have a negative contribution to the revenue, since the penalty fee is subtracted from the revenue. For example, there are penalties for a certain percentage of iron present in the cobalt concentrate for Ruashi Mining. In essence there are different ways of expressing the combined cut-off grade for the different minerals. The combined cut-off grade must also take into account the in-situ metal content (for both the main product and by-products), the mining and metallurgical factors, the cash cost and the price received for each product sold (Heugh, 2010).

It is important to check the calculation process of cut-off grade for a polymetallic deposit in order not to misclassify material. Wrongly derived formulae may result in what is shown in Figure 2.6 which shows a scatter plot of true values versus estimated values. The first quadrant shows ore which is lost due to an incorrect classification and the third quadrant shows waste that is incorrectly classified as ore. This demonstrates the importance of correctly determining the equivalent grade formula.

Cut-off grade calculation for a multi-mineral orebody is done using parametric cut-off grades. A parametric cut-off grade is one which is indirectly related to the grade distribution of the mineralised orebody. For a deposit like Ruashi with copper as the main mineral and cobalt, the by-product the grade is expressed in terms of the copper equivalent grade. This is done by calculating the cobalt equivalent grade in each copper category and adding the equivalent grade to the copper as shown below.

Cu Equivalent Grade

$$= \text{Grade}_{Cu} + \frac{Grade_{Co} * (Recovery_{Co} * (Price_{Co} - Selling\ Cost_{Co}) - Element\ Processing\ Cost_{Co})}{\text{Recovery}_{Cu} * (Price_{Cu} - Selling\ Cost_{Cu}) - Element\ Processing\ Cost_{Cu}}$$

Where:

Cu: copper

Co: cobalt

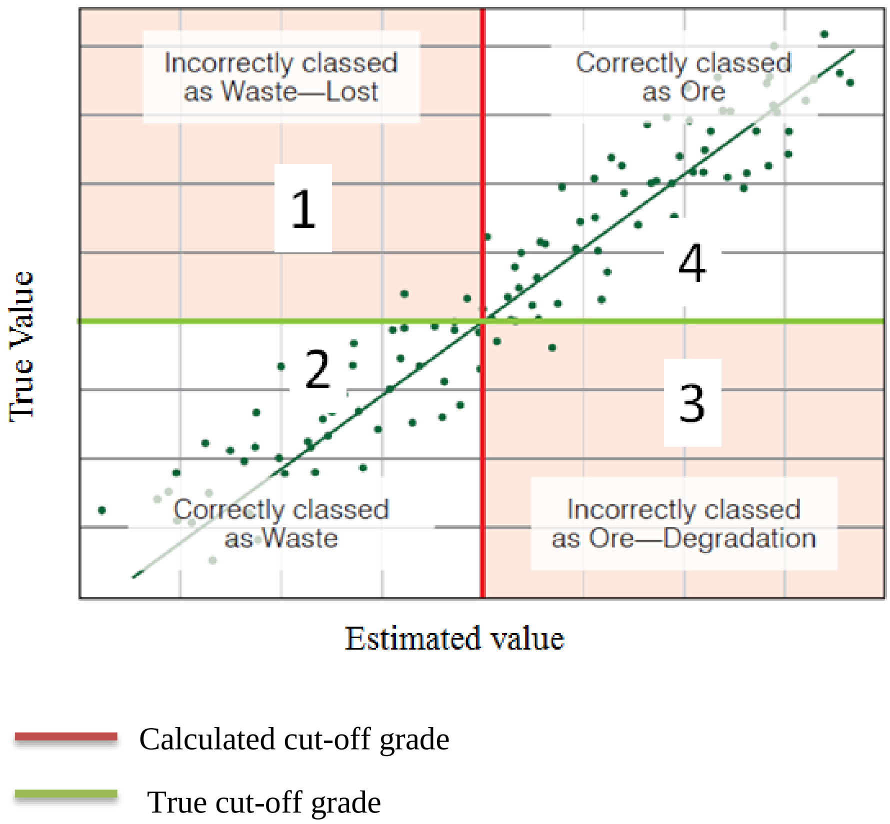


Figure 2.6: Plot of true and calculated values (Hall, 2014)

Once the mineralised body is represented as an equivalent grade, all analysis can continue as for a single mineral ore deposit (Lane, 1988). The following subsections give the different ways of dealing with various minerals in a polymetallic deposit.

2.6.1 Single grade cut-off approach

Baird and Satchwell (2001) give the following formula to be used for a theoretical break-even cut-off grade when other metal credits and penalties are taken into consideration. In this approach, by-products do not attract costs. The costs are all allocated to the primary product, but these costs are offset by the revenue received from the by-products.

Cut-off grade = (Ct – Cr) 100/(re(P – Cb)

Where:

Ct = cost per tonne for mining and milling and overhead

Cr = net credits (sum of by-products unit revenue minus total penalties per unit)

Cb = cost per pound for freight, tolling and refining.

P = commodity price per pound

r = the metallurgical recovery

e = 2 204.6 lb/t

They also suggest that the credits and penalties may be calculated using the average grades for the respective by-products and penalty elements for the optimised pit. However, they point out that this may generate cut-off grades that are impractical due to the by-products contribution. The formula does not provide for capital recovery.

2.6.2 The equivalent cut-off grade approach

The combined grade of the metals is expressed in terms of the primary metal, and this is called the primary metal equivalent grade. It involves calculating the value of the by-products (positive or negative) and then calculating what this is equivalent to in terms of the primary metal. The equivalent grade must be calculated for each block in the model based on assumed prices and recovery to treat the by-products. This metal equivalent grade is then applied to the resource (Baird & Satchwell, 2001).

2.6.3 Dollar value cut-off grade approach

The polymetallic grade can be expressed in different intrinsic values. According to Hall (2014), the grade of a polymetallic deposit can be expressed as an in situ value, recoverable value or payable value. The in situ value is calculated by multiplying the metal prices by the respective grades of any block. This ignores the possible recoveries of the various metals. The recoverable value (also called the net smelter return) takes into account the metallurgical recoveries in the calculation of the grade. The payable value approach takes into account all the metallurgical losses, product associated costs and payable proportions of the recovered products. The payable value approach is the method used in the SimSched software that is applied in this research. The author is of the opinion that the dollar value cut-off grade calculation method has to be augmented by other methods because it may result in impractical cut-off grade values due to the contribution of the other metals. In Ruashi's case, copper is the main product even though the price for cobalt is higher than that of copper. In blocks where the concentration of cobalt is higher in comparison with copper, the method will be biased towards cobalt by targeting the blocks with higher values and give rise to low copper grades that cannot be handled in leach.

2.7 Cut-off grade calculation considering environmental factors

Gholamnejad (2008) extends Lane's algorithm to cater for rehabilitation requirements. Emphasis is placed on minimising waste generation at source by maximising the utilisation of the resource. This approach favours the application of lower cut-off grades which results in higher amounts of ore being processed, thus generating lower amounts of waste materials to be dumped. The dumped waste attracts rehabilitation costs which add to operating costs. The rehabilitation cost is the unit cost of rehabilitating material of a particular type of waste rock after it has been dumped. Accounting for rehabilitation costs in cut-off grade derivation results in a decrease in the cut-off grade. This increases the amount of ore to be processed, resulting in the reduction of waste that is sent to the dump (Gholamnejad, 2008).

Environmental protection takes centre stage in modern mining with many non-governmental organisations being involved in policing mining operations in particular.

These organisations help local communities to force mining companies to adhere to environmental legislations and international environmental standards. They are also involved in ensuring that the communities have a say in granting the license to operate. Mining in general and particularly surface mining has negative impact on the environment due to waste disposal on the surface, primarily in the form of tailings and waste material structures such as tailings dams and waste dumps. The open pit itself leaves an irreparable scar on the surface since most operations do not backfill the pits at closure. Some of the waste materials may be acid generating. It is less expensive to eliminate or minimise waste generation at the source than to design mitigation measures after the waste has been generated. It is important to also consider environmental and social issues during the mine design stage. Table 2.2 shows the mutually dependent sources of increased value in mining operations. The optimal cut-off grade strategy and tactics are important considerations in an endeavour to increase the value of an operation.

Sustainable development calls for the application of improved and environmentally-friendly technologies. This must be incorporated into the plan before the project starts. The cut-off grade and the pit limits are sensitive to changes in revenue (e.g. metal price fluctuations) and costs (i.e. mining, milling, selling, taxes, mine decommissioning and mine closure) (Rashidinjad, Osanloo, & Rezai, 2009). The potential for acidic drainage is determined in the planning process and provision made to either segregate reactive wastes or blend acid generating material with inert material.

Table 2.2: Sources of increased value in mining operations (Gholamnejad, 2008)

Value Chain	▼ Infrastructure		
		Resources ▶	▪ Additional resources ▪ Exploiting marginal resources ▪ Better ranking systems ▪ Increased ore body knowledge
		Mining ▶	▪ Increasing mining capacity ▪ Optimal mining limits ▪ *Optimal cutoff grade strategy and tactics* ▪ Improved selectivity ▪ Better mining sequences ▪ Alternative mining methods ▪ New technology
		Processing ▶	▪ Alternative processing methods ▪ Optimal processing policies ▪ Processing waste streams ▪ Increased processing rates ▪ New technology
		Marketing ▶	▪ Blending opportunities ▪ Introducing new products ▪ New by-products ▪ Penetrating new markets
	▪ Power ▪ Water (liability/asset) ▪ Transport options ▪ Land ▪ Closure		

Taking rehabilitation costs into account can decrease the cut-off grade resulting in an increased amount of ore that is processed and a decrease in the waste to be sent to the waste dump (Gholamnejad, 2008). Ruashi Mining is mill capacity constrained, hence the cut-off grade calculation which considers environmental cost is derived from Gholamnejad (2008) as given in the following equation:

The symbols used are

T = production period (e.g. a year)

C = mill capacity (tonnes per period)

m = unit mining cost ($/t of material mined)

r = selling cost ($/t of product

h = rehabilitation cost ($/t of rehabilitated material)

f = fixed costs per period

s = selling price ($/tonne of product)

y = recovery

Qm = quantity mined

Qc = quantity milled per period

Qr = quantity of product produced

The cut-off grade when the mill is the bottleneck is given by:

Cut-off grade = (c + f/C – h)/ ((s – r)*y)

The inclusion of the environment costs lowers the cut-off grade in order to reduce the amount of waste discarded at the waste dump.

2.8 Mining royalties and tax

The so-called resources curse or paradox of poverty in the midst of plenty refers to the paradox that countries and regions with an abundance of natural resources, non-renewable resources like minerals and fuels, tend to have less economic growth and worse development outcomes than countries with fewer or no natural resources (Maxwell, 2013). Resource-rich economies constantly face changing commodity prices resulting in revenue volatility. Volatile mineral prices are partly responsible for the resource curse as fluctuating government revenues linked to unstable commodity prices may impede long-term planning and prudent fiscal policy.

According to Ricardo (1821), “Rent is that portion of produce of the earth which is paid to the landlord for the use of the original and indestructible powers of the soil.” Therefore, the rent for mines is that payment which is made for the minerals removed from the earth (Minnitt, 2015). Mineral resources rent vary in direct proportion to the price cycle.

According Maxwell (2013), a country's dependence on mineral resources rent leads to unsustainable currency appreciation and fosters consumption rather than diversification and sustainable economic growth. This also discourages productive investment outside the non-rent sector and encourages rent-seeking and predatory behaviour by government. The lack of investment in other sectors of the economy has the pernicious effect known in mineral economics circles as the Dutch disease. Companies expect governments to use mineral revenues effectively for the benefit of the community in order to enhance a good image within communities. Arguably, if public revenues from mining are spent effectively and in a transparent manner, there would be less or no pressure from local communities to provide infrastructure and services normally provided by the public sector (Corden & Neary, 1982).

Harman and Guj (2013) suggest that mining companies should be subjected to special taxes different from other industries because they cause the depletion of non-renewable resources and the public as the owners of the natural resources must also benefit. The owner of mineral resources may acquire economic rents either by undertaking mining activity directly or through an agreement with another party. Governments are normally the custodian of the resources on behalf of the community. Governments do not normally extract the resources directly, but they lease the extraction of these resources to private companies. The private companies then pay royalty taxes to the government so that the local communities can also benefit from the resources. Royalties are a payment for the transfer of ownership of the resource from the community to the tenement holder. Different countries have different royalty and tax regimes for the mining industry and for different commodities.

There are several types of tax in the minerals sector. They include specific (unit-based) royalties, ad valorem (value of production-based) royalties, accounting profit-based taxes and resource rent taxes. Specific (unit-based) royalties are levied on a tax base relating to the physical rather than a financial measure of a mineral resource, for example, dollars per tonne. Ad valorem royalties consist of a uniform percentage (the rate) of the gross sale price (the base) of a mineral product where the sale is made by the entity that extracted the resource (Harman & Guj, 2013).

Birch (2016) points out that the mineral royalty tax is applied to the total mineral sales revenue regardless of whether the operation makes profit or not. The mineral resources royalty tax must be accounted for in cut-off grade calculation. It is considered as a cost because it is levied on total revenue. The royalty tax results in an increase in cut-off grade due to an increase in costs which in turn results in reduced reserves and hence a shorter mine life. On the other hand, income tax is calculated on profits and does not affect the economic behaviour of the mining business. Some governments charge higher royalties for unrefined commodities while others impose a levy to force companies to add value to commodities before export. Mangondo (2006) argues that a good tax regime should not disturb economic behaviour (Birch, 2016).

In the Democratic Republic of Congo (DRC), the highest marginal corporate income tax for corporations is 35%, but mining companies are subjected to 30% levied on net profits of the company. The export of copper and cobalt concentrates was banned in 2013 to force mining companies to process and refine these metals domestically. The royalty is paid from the date of commencement of exploitation and is 2% for copper (KPMG, 2013/14). However, the government set up a mining company called Gecamines which oversees the mining of copper in the country. Ruashi Mining also pays royalty to Gecamines with the total royalty adding up to 3.6%.

2.9 Capacity constraints

Lane (1988) divided a whole mining operation into three stages namely mining, processing and marketing. In surface operations, the mining stage comprises drilling and blasting, loading and hauling. The processing or treating stage consists of crushing, grinding and separation (or concentration). Marketing is made up of smelting, refining, and selling (Lane, 1988). This subdivision of the operation makes it easier to analyse it for cut-off grade optimisation. Mining is a capital-intensive business with long lead times before the return on capital employed is realised. Capital is also scarce in the current hard economic times where commodity prices are more volatile than before. The size of the deposit and the extraction rate determine the size of the operation. This implies that one of the stages or a combination has a limited capacity. The stage with the limited capacity forms the bottleneck of the operation. It is prudent to fully utilise that stage which has limited capacity. This brings the issue of opportunity cost; a loss incurred by an investor for tying up capital in the present mining operation instead of investing in another more lucrative undertaking (Minnitt, 2004). According to Rendu (2008), the opportunity costs or benefits result from mining and processing material not previously scheduled for processing thereby displacing higher grade material. Opportunity costs are only incurred where the operation is capacity constrained or has a bottleneck.

Wooller (2001) concurs with Lane (1988) by pointing out that cut-off grade optimisation maximises the NPV of a project based on capacity constraints on the mine, the mill, and the market. The capacity constraints are expressed as annual limits to the material handled by the respective stage of the mining process. This is true because constraints arise due to the scarcity of capital. If capital was ubiquitous, then the processes would be overdesigned for flexibility. In the case of limited capacity, the sacrificing of low-grade material enables the mill to process higher grade ore that delivers a higher cash flow. Reducing the residence time of ore in the mill results in a higher tonnage throughput but at a lower metal recovery. This is arguably not the efficient utilisation of resources although the net result is an increase in the rate of metal production and cash flow (Wooller, 2001). As argued earlier, this is wasteful and is not sustainable. The solution could be blending opportunities between high- and low-grade ore which enables the efficient and effective utilisation of the mineral resources. If the cut-off grade applied is too high, the overall resource would be too small and economic material would be sent to the waste dump. The mine and processing plant capacity would be uneconomically overused in case of too low a cut-off grade (Abdollahisharif, Bakhtavart, & Anemangely, 2012). Pasieka and Sotirow (1985) assert that in strategic planning it is necessary to be adaptable and think ‘out of the box’ by varying capacities. Existing capacities should be considered but never accepted as limitations for long-term cut-off grade determination. Varying operational capacities enable the justification of capital expenditures if there is value-add for increased capacities. It is also necessary to consider other treatment alternatives. These views should be taken into account particularly in view of scarce capital. Lane (1988) derived formulae for the analysis of cut-off grades in the presence of capacity constraints. This gives rise to six optimum cut-off grades depending on which capacity is the bottleneck. These cut-off grades are classified into two groups each with three types of cut-off grade. They are limiting cut-off grades and the balancing cut-off grades. The three limiting cut-off grades are based on break-even formulae depending on which stage is independently the bottleneck in the production process. The balancing cut-off grades arise when two production stages simultaneously operate at full capacity. The limiting cut-off grades are the mining-limited, treatment-limited and marketing-limited cut-off grades. The balancing cut-off grades are mining-and-treatment-limited, mining-and-marketing-limited and treatment-and-marketing-limited cut-off grades (Hall, 2014). The bottleneck at Ruashi Mining is the mill capacity. So according to Lane (1988), the Ruashi operation is treatment-limited. The products (copper and cobalt) have ready markets, and the mining capacity is beyond the current treatment capacity.

2.10 Cut-off grade optimisation

Optimisation of the corporate business plan for an operation or multiple operations must take account of the complete process stream, from having the mineralisation identified and described by geologists to final sale and receipt of revenue. The use of declining cut-off grades is usually mistakenly assumed to cause high-grading. This may hold true if an artificially high discount rate is used in the cut-off grade optimisation process (Border, 1991). However, Birch argues that optimising on NPV may give rise to the temptation to focus on short-term at the expense of longer-term gains (Birch, 2016).

Birch (2015) concurs with Dagdelen and Mohammed (1997) when he points out that the break-even cut-off grade can be used in defining reserves since mining and processing all the economic ore enable the company to maximise the undiscounted profits from a mining venture. However, if break-even cut-off grade is used to determine immediate processing of given ore this may result in a suboptimal schedule given that the NPV is not optimised in this instance, (Dagdelen & Mohammed, 1997). This emphasises the need to separate pit optimisation from production scheduling. The break-even cut-off grade is used to determine the ultimate pit during pit optimisation. Once the pit shape has been determined and a design made, then cut-off grade optimisation is conducted on material inside the pit in order to maximise the present value of the operation. The present value can be maximised by implementing a cut-off grade strategy throughout the life of the mine. It is a dynamic process. Treating lower grade material with a grade slightly above the break-even cut-off grade in the earlier life of the mine displaces higher grade ore. Higher grade ore makes more profit, and hence it is prudent to treat it at the beginning of the mine life. Higher grade material must be prioritised in the processing decision in order to maximise the NPV. This approach leads to declining cut-off grade over time (Crone & Hunter, 1992). Nieto and Bascetin (2006) also reinforce this idea when they postulate that cut-off grade optimisation maximises the profit of a mine by stockpiling low grade ore at the start of the mine life. The high grade ore sent to the mill results in higher cash flow at the beginning of the mine life (Nieto & Bascetin, 2006). Rendu (2008) also builds on this idea, asserting that since the cut-off grade defines both the profitability and the life of the mine, a high cut-off grade increases short term profitability and NPV but decreases the mine life. Increased cut-off grades are normally applied so as to reduce political risk. This is because the company achieves higher financial return over a very short period of time. High cut-off grade results in the wasting of low grade material that can be processed at the end of the mine life when the higher grade ore is depleted, particularly in cases where there is no option to stockpile for treatment later, (Rendu, 2008).

More recently, Hall (2014) argued that cut-off grade optimisation must not be divorced from the rest of the overall mine planning process, implying that the cut-off grade must not be calculated before the optimisation process. In reality, the cut-off grade is one of the outputs to the strategic optimisation process. “The mine strategy optimisation process is a multi-dimensional analysis that is accounting for everything of importance. It seeks to identify the best combination simultaneously of cut-off grades and other design and strategic decision parameters in order to achieve the corporate goal” (Hall, 2014, p. 102). This means that the corporate goal should be specified on the onset of planning for a mining operation. It is possible to increase the cut-off grade until an optimum value is achieved as illustrated in Figure 2.7. Adopting grades that are higher than the cut-off grade may result in the destruction of value when valuable material ends up being discarded as waste.

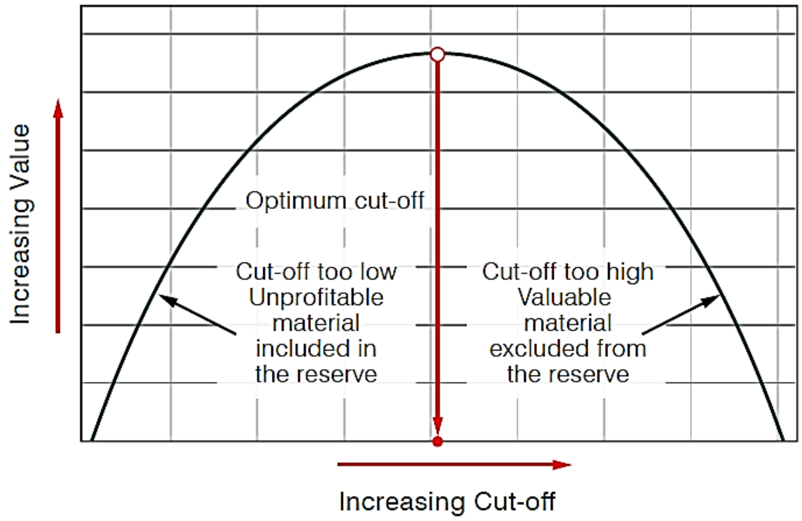


Figure 2.7: Generic value versus cut-off curve (Hall, 2014)

It is important to get the best possible value for the company. This can only be done by optimising the important parameters simultaneously. For example, the cut-off grade and production can be optimised together in order to get the optimum value for the company. This approach gives a three dimensional surface with a peak, which is called a hill of value, (Hall, 2014). This is shown in Figure 2.8.

Hall (2014) developed a method for optimising cut-off grade based on the various limiting factors by simplifying Lane's (1988) complex mathematical formulas which previously dissuaded the desire to pursue this important subject for so many years.

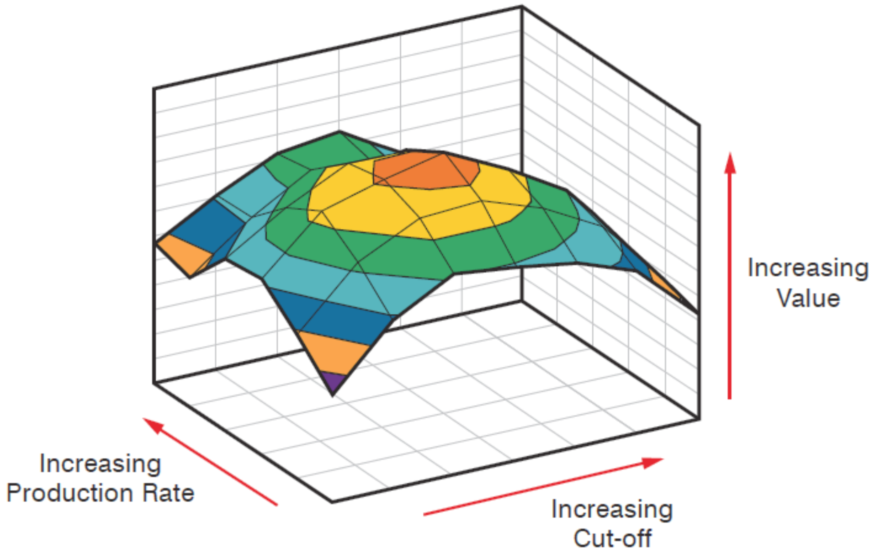


Figure 2.8: A typical underground hill of value versus cut-off and production targets (Hall, 2014)

According to Lane (1988) cited in Dagdelen and Mohammed (1997), the cut-off grade equation that maximizes the NPV of the cash flows coming from the deposit when the mill capacity is limited is given as:

$g_{opt}(i) = (c + f + F(i))/(P – s) \times y$

Where i =1, ... N (mine life), and $g_{opt}(i)$ is the cut-off grade to be used in year i; F(i) is the opportunity cost per ton of material milled in year i and it is defined as:

$F(i) = (d \times NPV(i))/C$

where NPV (i) is NPV of future cash flows of the years i through to the end of mine life N; d is the discount rate; and C is the total milling capacity in year i. The f is the fixed costs per ton ore milled in a year and it is defined as:

$f = f_a/C$

Where f_a, is the annual fixed costs.

Clearly, the determination of the mining operation NPV at a given point is an iterative one. The initial NPV is assumed to be zero so as to be able to calculate the initial cut-off grade. This initial cut-off grade is then used to run the iteration to generate NPVs for the coming years and hence a cash flow schedule. Iterations continue until the cut-off grade strategy and the resulting cash flows converge and stay constant.

Since cut-off grade optimisation tends to discard low grade material between the cut-off grade and the break-even cut-off grade, the ore feed to the mill is reduced. But the same amount of material is mined from the pit. The metal recovered is also reduced. The life of the mine is significantly reduced compared to the break-even cut-off. If the stockpiling was allowed, then the stockpiled material has to be worked into the mining schedule or processed at the end of the mine life. The cut-off grade optimisation with the stockpiling policy further enhances the NPV of a given mining project (Dagdelen & Mohammed, 1997).

The discounted cash flow or NPV is a better measure of profitability than straight cash flow because it takes into account the time value of money. Cut-off grade optimisation gives a shorter project payback period for the initial investment. The value of a project is increased by increasing early cash flows at the expense of later cash flows. It is, however, important to point out that high cut-offs in the first years of an operation also result in high stripping ratios (Whittle & Wharton, 1995). As such in order to maximize the project NPV, it is important to use dynamic cut-off grades, rather than the constant breakeven cut-off grade.

2.11 Cut-off grade with option to stockpile

Dagdelen and Mohammed (1997) show that the break-even cut-off grade is used for defining ore reserves. Scheduling the application of the break-even cut-off grade gives a sub-optimal schedule if the process is capacity constrained. The cut-off grade that maximises the NPV of an operation with capacity constraints is much higher than the break-even cut-off grade. The magnitude of the optimum cut-off grade is determined by the opportunity costs and the grade distribution of the deposit. Mineralised material classified as waste at the beginning of the life of mine may become economic towards the end of life of the mine and may then be processed, (Asad, 2005). The optimised cut-off grade initially takes values much higher than the break-even grade. This implies that grades which are marginally economic to process at the beginning of the mine life due to availability of higher economic value ore can be treated later when the higher grade ore gets depleted. This material with grades between the optimum grade and break-even grade is therefore stockpiled for later processing. Economic analysis of processing the stockpiles has to be done also in the same way as it is done for mining (Dagdelen & Mohammed, 1997). This gives rise to dynamic optimum cut-off grades which decline with time as the reserves get depleted. Metal prices and operating costs change during the mine life. This declining NPV favours higher cut-off grades in the earlier years of life of mine and lower cut-off grades in the later years.

Smith (2012) however warns against unnecessarily too high cut-off grades, stressing that filling plant capacity with optimum grade ore can only be implemented if the plant operates at full capacity and also helps avoid sterilising reserves in the pit by high-grading. The use of stockpiles means that intermediate grades are not lost, but merely deferred for later processing, albeit with a cost for re-handling and possibly with reduced recoveries due to degradation with time (Wharton, 1996). Stockpiles are generated throughout the life of the mine. However, there are options to make use of the stockpiles in parallel to the ore coming from the pit or they can be processed later when the pit is depleted (Asad & Topal, 2011). Whittle and Whittle (2007) also pointed out that if it is feasible to stockpile the lower grade material and process it later, then the negative effects of raising the cut-off grade are lessened. If stockpiling is implemented, there will not be any loss of overall life of the project as all the material over the marginal cut-off grade will eventually be processed. The cost of re-handling and any change in recovery due to further oxidisation of stockpiled material must be taken into account in the calculations (Whittle & Whittle, 2007).

2.12 Price and revenue

This research will not be complete without addressing the issue of price and revenue. These are pivotal in the maximisation of economic earnings through the cut-off grade strategy (Khodayari & Jafarnejad, 2012). It is extremely difficult to confidently predict the long-term trend in metal prices due to the current and constantly high economic and political instability. This is why it is necessary to update the long-term cut-off grade on an annual basis and adjust the ore reserves based on the new cut-off grade. The long-term forecast price must take into consideration the available technological, business and political intelligence of demand-supply related parameters (Sinding & Larsen, 1995).

In instances where an orebody hosts more than one mineral, an allowance must be made in the revenue for the contribution of each by-product in the cut-off grade calculation. In many cases metallurgical recoveries vary with the variation in mill feed grade. In addition, most commodities are currently experiencing historic low prices. Prices affect the value of material in the pit. Increase in price increases the value of lower grade material which might make it minable under the prevailing price and cost conditions. Higher metal prices, therefore, lower the marginal cut-off grade and vice versa. In turn, when prices increase, reserves also increase as a result of the decrease in cut-off grade (Khodayari & Jafarnejad, 2012).

2.13 Risk

The common adage that mining is a risky business is true. Risk stems from the inability to accurately predict the future. Whilst many authors have written many books and papers on the subject, it is beyond the scope of this report to delve much into this well-researched and documented topic. The main aim of this section is to briefly discuss risk as it applies to cut-off grade optimisation.

In his definition which denotes that risk can be quantified, Heuberger (2005) defines risk as the amount of uncertainty in the outcome of a result. There are many types of risk which investors consider for their investments. Political Risk refers to the possibility that investment returns could suffer as a result of political changes or instability in a country. Instability affecting investment returns could stem from a change in government, legislative bodies, other foreign policy makers, or military control. Political risk becomes a significant factor as the time horizon of an investment gets longer. The outcome of political risk could drag down investment returns or even go so far as to remove the ability to withdraw capital from an investment (Birch, 2015). Country risk encompasses a collection of risks associated with investing in a foreign country. These risks include political risk, exchange rate risk, economic risk, sovereign risk and transfer risk, which is the risk of capital being locked up or frozen by government action. Country risk varies from one country to another. Some countries have high enough risk to discourage much foreign investment. Country risk can reduce the expected return on an investment and must be taken into consideration whenever investing abroad. Some country risks do not have an effective hedge. Other types of risk, such as exchange rate related ones, can be protected against with a marginal loss of profit potential. The United States of America (USA) is generally considered the benchmark for low country risk and most nations can have their risk measured as compared to the USA. Country risk is higher with longer term investments and direct investments, which are investments not made through a regulated market or exchange (Anon, 2015).

The software called @Risk is used for modelling and analysing risk in Microsoft Excel. @Risk is useful in developing risk models, identifying uncertainty and then using simulation to conduct risk analysis (Anon, 2004). The modelling produces options from which decisions can be made. The use of options enhances the likelihood of achieving the planned return on investment and optimises the achieved returns. Commodity prices cannot be predicted with certainty. If prices change, the mine plan also changes in line with the changes in the reserves. For a bimetallic deposit like Ruashi, it is prudent to channel more resources to the product with the higher price and less for the lower price product. The way in which an operation adjusts to changes in the operating environment determines its risk (Runge, 1998). According to Runge (1998), @Risk aims to critique the worst case scenario in order to be ready for any eventualities.

2.14 Opportunity costs

As stated earlier, opportunity cost is a loss incurred by an investor for tying up capital in the present mining operation instead of investing in another more lucrative undertaking (Minnitt, 2004). Opportunity cost involves the delay in the realisation of income as a result of processing unscheduled ore in preference of the scheduled ore. It is incurred due to bottlenecks in the production system. High opportunity costs result in high cut-off grade. Ultimately, there would be no opportunity costs if there were no constraints. Constraints are caused by the scarcity of capital or bad designs. If capital was available then the production system would be overdesigned (Rendu, 2008).

Further, opportunity costs or benefits may result from mining and processing material not previously scheduled for processing. No opportunity cost is incurred if there are no capacity constraints. This is because adding one more tonne to the process will have no impact on previously expected cash flows. An opportunity cost is the cost of an alternative that must be forgone in order to pursue a certain action, meaning the benefits one could have received by taking an alternative action. If there is capacity constraint, the opportunity cost includes the cost of displacing high grade material already scheduled for processing and postponing treatment of this material (Lane, 1988).

2.15 Modifying factors

Besides the factors that have been stated before like cost, revenue and marketing, there are other modifying factors which are applied to a mineral resource in order to generate reserves. These include mining and metallurgical recoveries, dilution and geotechnical parameters (Appleyard & Smith, 2001). It is crucial to be able to measure the mining recovery which may be distorted by an overestimation of metal content or inaccurate density. It is also important to have good sampling standards in place in order to be able to account for the metal. Mining and processing plant production need to be compared through mine to mill reconciliation. This also aids metal accounting and analyses estimates from the resource and grade control models (Tetteh & Cawood, 2015).

Elbrond (1994) points out that even though the builder of a resource is highly skilled the resulting model he delivers will never exactly model the real deposit as it appears in reality. This is because the delineation process may include some waste into the deposit and exclude some ore (Elbrond, 1994).

2.16 Multiple process options

Multiple processes in a mining operation require that cut-off grades be calculated to distinguish between ore and waste. For example, ore sent to the leach pad may be of lower cut-off grade compared to ore that is sent to the flotation plant. Deciding among the processes involves determining the differences between the values derived from each of them. The material of a particular grade may then be sent to the process that produces the highest value from that particular material. The variations among the varied processes result from differences in the cost regimes, metallurgical processes and recoveries, and the product characteristics. Product quality may vary which might also results in different prices for the respective products (Rendu, 2008).

2.17 Discount rate

Nhleko and Musingwini (2016) define discount rate as the weighted sum of the cost of debt and equity. It is not the intention of this research to delve much into the specifics of discount rate calculations. The reader is referred to the many articles by other authors on the same topic. It is in the discount rate that project risk is accounted for. The discount rate is vital for the value of mineral projects. However, the determination of the discount rate depends on subjective perception of the degree of risk and other past experience factors (Park & Matunhire, 2011).

The discount rate is an indicator of the investors' confidence in a particular project where a low discount rate shows investor confidence with the future and increases the present value of the project. Where investors perceive risk they tend to advocate for a high discount rate at the expense of the NPV. The aim is to recoup the investment as quickly as possible and move out of the risky project (Runge, 1998). From the above, it is clear that high NPV favours high cut-off grades. This is reflected in the declining cut-off grades strategies.

2.18 Throughput and hardness

The metal output also depends on the mill throughput. The higher the mill throughput at a particular grade, the higher the metal output, all other factors being constant. The mill throughput is affected by ore hardness and the milling circuit power (Prasetya & Simatupang, 2012). The metal recovered depends on the metal input into the system. If more metal cannot be availed by the rated throughput, most operations will resort to increasing the input metal by increasing the cut-off grade.

2.19 Leach time

The time in which the ore resides in the leach tanks determines how much of the material can be recovered. More resident time means more metal is dissolved from the gangue. However, an optimum resident time needs to be determined in order not to sacrifice metal output. The higher the resident time the lower the cut-off grade required. However, this is not a linear relationship. According to Padilla, Cirsternas and Cueto (2008), leaching time among other factors affects both the recovery and the capacity of the leaching operation. Their observation also showed that the optimum recovery is not necessarily the maximum recovery (Padilla, Cirsternas, & Cueto, 2008). This indicates that it might be required to increase the cut-off grade but reduce the leaching time in order to achieve optimum metal production.

2.20 Chapter 2 summary

The review of the literature on cut-off grade has shown that there has been a lot of research done on this topic since the ground breaking documents from Lane. Generally, Lane's work is the foundation for the study of cut-off grade calculation. The determination of cut-off grade is actually the economic definition of ore. The cut-off grade is the main driver of value in a mining operation. It is used to estimate reserves for a mining operation and determines the life of a mine. However, there are many stakeholders with diverging interests on the mining operation. The cut-off grade must be determined with all these interests in mind which can be a complex process.

It has been shown that the external cut-off grade is used to determine the pit limits. One such grade is the break-even grade which is used to determine the pit limits or stope shape. Once the stope shape or pit limit has been determined, the internal cut-off grades are applied to material inside the pit to determine the reserves. Most operations use the external cut-off grade throughout. There are various ways of expressing the grade of a polymetallic deposit. Each of them has its own advantages and disadvantages. The payable value grade expresses the grade of the polymetallic deposit in terms of value to be recovered should the ore blocks be mined. This is the concept used in the SimSched software which is used in this study. Stockpiling maximises the utilisation of the resource by keeping the material with grades between break-even and the optimal cut-off grade, thus extending the life of the processing facilities. The work that has been done shows that consideration of environmental factors favours a lower cut-off grade in order to reduce the waste that is generated. The cut-off grade strategy that results in higher NPV for a given project starts with high cut-off grades during the initial years of the deposit. As the deposit matures the cut-off grades gradually decline to breakeven cut-off grade depending upon the grade distribution of the deposit.

CHAPTER 3: METHODOLOGY

3.1 Chapter overview

This chapter describes the methodology that has been employed for the research. The few methods and software selected are presented in this chapter. There is some manipulation that needs to be done to the Ruashi block model for it to be usable in some of the software. The first is the break-even cut-off grade calculated in an excel spreadsheet to show the impact of pursuing the break-even cut-off grade policy. Ruashi Mining currently uses MineSched for life of mine scheduling. The NPVS is used in this study in order to optimise the extraction of both copper and cobalt without resorting to parametric cut-off grades. Finally, the use of SimSched is also explained and the expected results outlined. Blending and stockpiling are also given since there are huge low grade stockpiles at Ruashi. The research also looks at the postponement of waste dump rehabilitation in a bid to increase the NPV and lower the cut-off grade to optimise the resource utilisation. Findings from these may guide Ruashi in the strategic planning of the operation. The use of @Risk software is also described to show how the software will be used to conduct risk analysis on results from SimSched DBS.

3.2 Break-even analysis

The break-even cut-off grade is the grade at which the realised revenue balances out the incurred costs of generating that revenue. The break-even cut-off grade is based on the principle of breaking even and not adding value (Birch, 2015). There are various break-even cut-off grades depending on the costs used in the calculations. The marginal break-even cut-off grades will be calculated using the processing and refining variable costs since the Ruashi operation is mill capacity constrained. The contribution of each of the two products is then analysed to investigate its contribution to the cash flow. The break-even cut-off grade is the grade at which the NPV is equal to zero. Since the pit optimisation has already been done the break-even analysis will be based on variable costs only. The two types of break-even are shown in Figure 3.1.

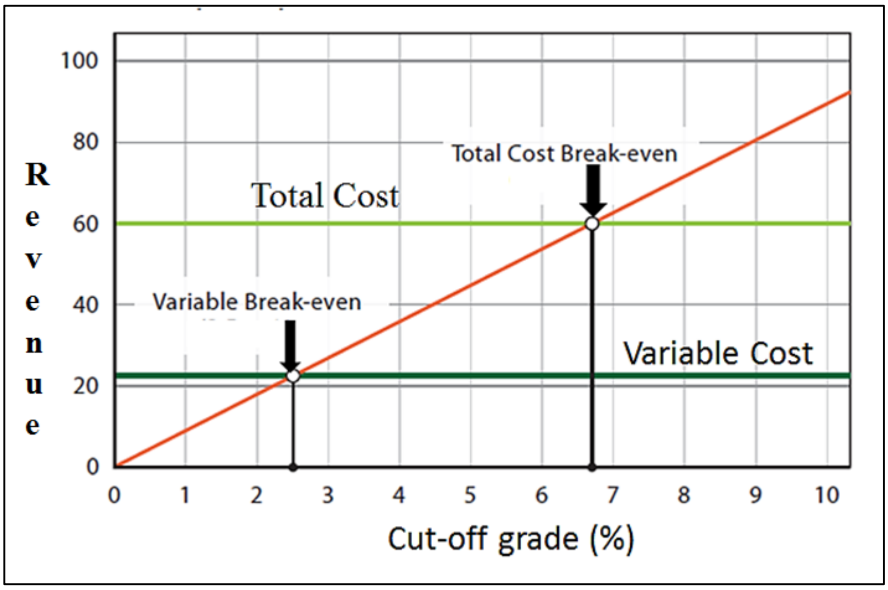


Figure 3.1: Break even points for unit total and unit variable costs (Hall, 2014)

The NPV of cash flow based on the break-even cut-off grade is also considered in the life of the mine. This is mainly to show the effect of running an operation on break-even cut-off grade. The results will be tabulated in spreadsheets.

3.3 NPV Scheduler pit optimisation

Lerchs and Grossmann in 1964 published a mathematical method for the determination of the optimal shape of an open pit in three dimensions. This used in an orebody block model to generate lists of related blocks that should, or should not be mined. The final list describes the pit with the highest possible total value, subject to the required pit slopes. The NPVS program uses the same Lerchs-Grossmann technique to produce a set of nested optimal pits. Each pit is optimal for a different set of value ratios, and these are used to guide different mining schedules. Financial analysis of these schedules, with discounted cash flows, allows selection and sensitivity analysis of the best pit according to different criteria set by the operation (Gawthorpe, 2005).

The cut-off grade optimisation strategy in NPVs is the declining cut-off grade given by:

Cut-off grade = (h+(f+F)/H)/((p-k) *y)

Where:

h = milling cost ($/t)

f = fixed costs per annum ($/year)

F = Opportunity cost ($/year)

H = mill capacity (t/year)

p = price ($/t)

k = marketing cost ($/tonne of metal

y = plant recovery (%)

The results from the cut-off grade optimisation are incorporated into a spreadsheet to determine the life of mine NPV.

3.4 MineSched life of mine schedule

MineSched is used to automatically generate long-term plans that respect input constraints specified by the user. MineSched blends material from stockpiles, processing plants, and waste dumps, producing schedules with complete reports and graphical results. MineSched also creates schedules that meet quality and material ratio targets while considering practical mining constraints and suitable mining methods. MineSched is a target-based scheduling algorithm which automatically creates a sequence that tries to meet the targets while adhering to set rules. Figure 3.2 shows a typical Minesched set-up for ore supply and destinations with material targets.

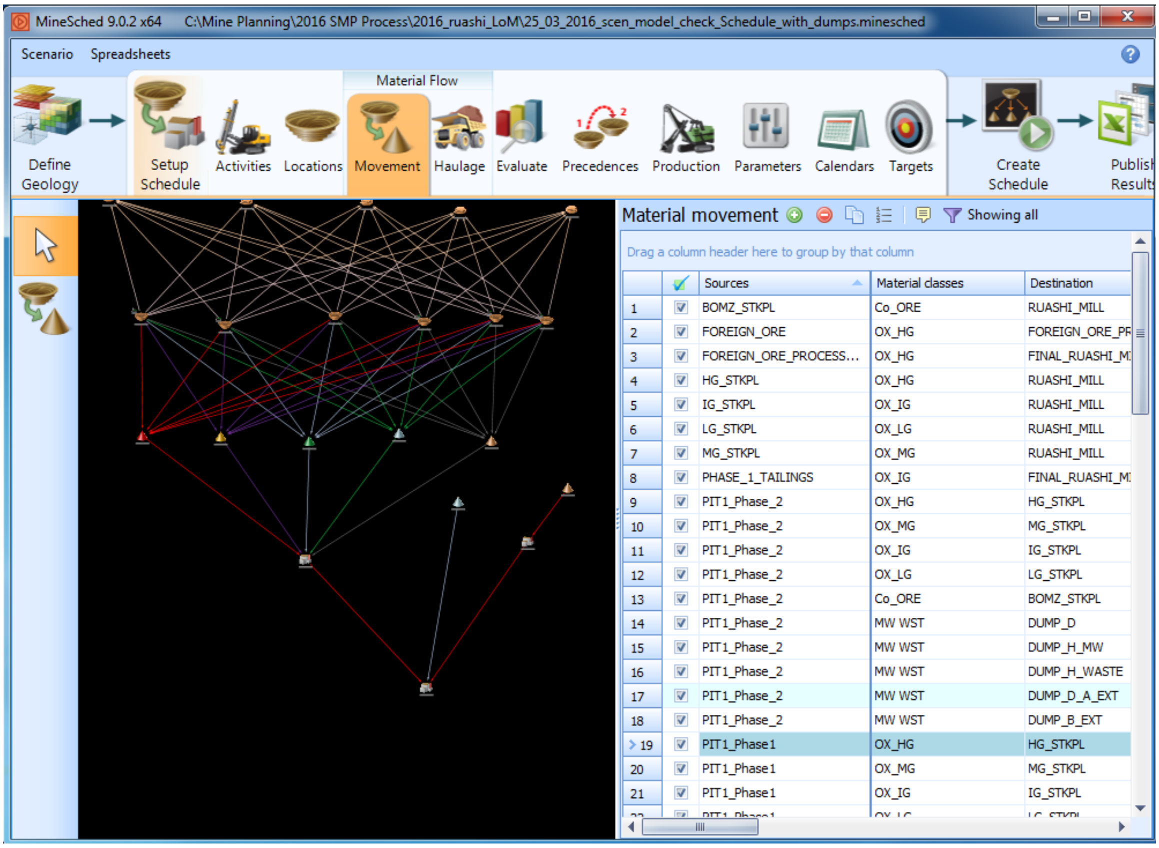


Figure 3.2: Typical Minesched setup

3.5 SimSched life of mine schedule

Direct block scheduling allows a complete schedule to be executed directly from the block model. The scheduler finds a mining plan that maximises the NPV of the project. This report is based on the scheduling of material inside the current Ruashi pit design. This file must have a header without special characters with fields separated by commas and using dot notation as the decimal separator. Air blocks are removed in order for the software to identify the topography. The metric system is used as units for imported data.

The required fields for each block are:

 Indices on X, Y and Z;

 Grades; and

 Economic values.

Figure 3.3 shows a schematic block model for scheduling in SimSched.

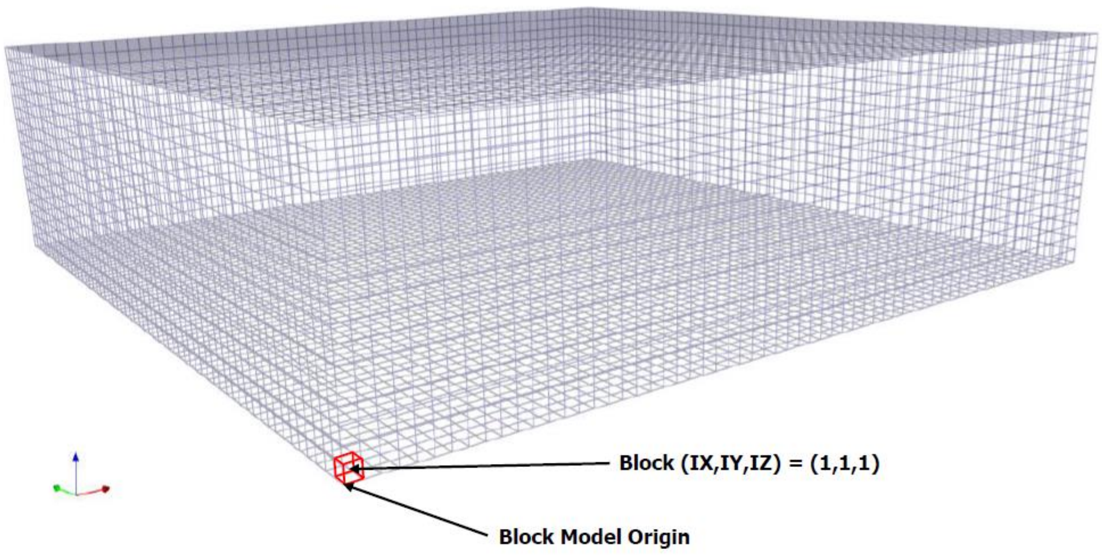


Figure 3.3: Typical block model for SimSched scheduling

The indices of each block represent its position in the model, indicating in which column line and level (IX, IY and IZ) it is. The indices must be integer values, starting with any value. The model's origin is located in the minimum coordinates at X, Y and Z. Each block must have associated economic values related to it being sent to either process or waste dumps

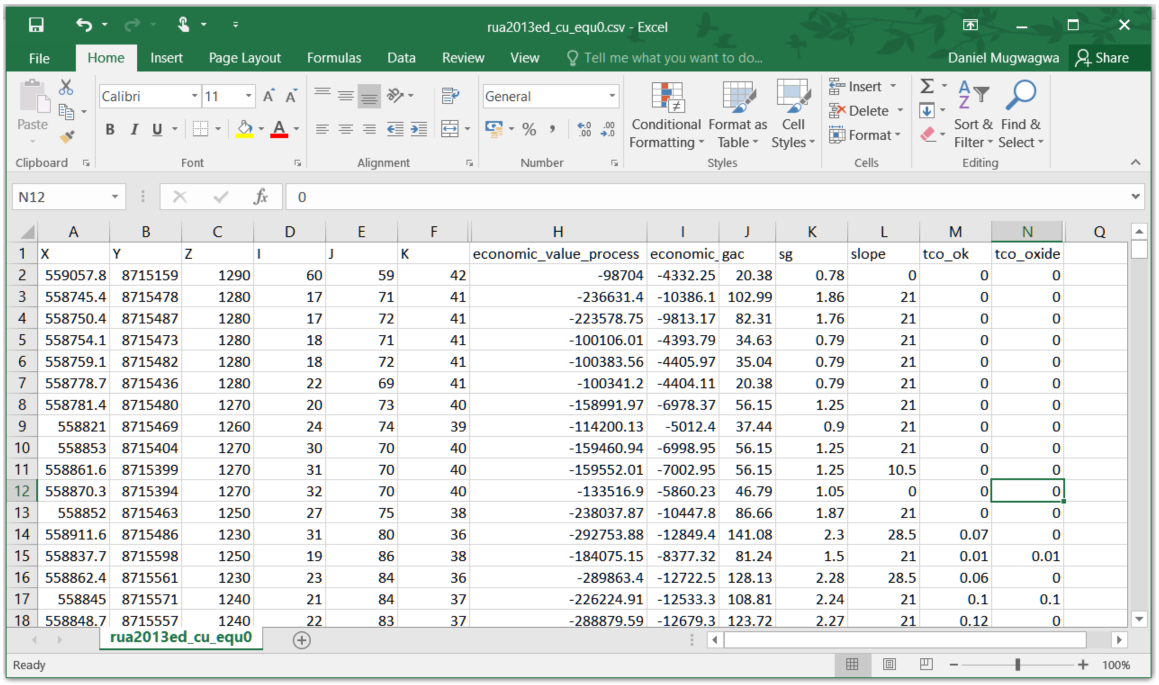
Other optional fields:

 Density (t/m^3).

 Slope angle (degrees).

 Process recoveries (values from 0 to 1).

Figure 3.4 shows a typical model prepared for input into SimSched for scheduling.



	A	B	C	D	E	F	H	I	J	K	L	M	N
1	X	Y	Z	I	J	K	economic_value_process	economic_	gac	sg	slope	tco_ok	tco_oxide
2	559057.8	8715159	1290	60	59	42	-98704	-4332.25	20.38	0.78	0	0	0
3	558745.4	8715478	1280	17	71	41	-236631.4	-10386.1	102.99	1.86	21	0	0
4	558750.4	8715487	1280	17	72	41	-223578.75	-9813.17	82.31	1.76	21	0	0
5	558754.1	8715473	1280	18	71	41	-100106.01	-4393.79	34.63	0.79	21	0	0
6	558759.1	8715482	1280	18	72	41	-100383.56	-4405.97	35.04	0.79	21	0	0
7	558778.7	8715436	1280	22	69	41	-100341.2	-4404.11	20.38	0.79	21	0	0
8	558781.4	8715480	1270	20	73	40	-158991.97	-6978.37	56.15	1.25	21	0	0
9	558821	8715469	1260	24	74	39	-114200.13	-5012.4	37.44	0.9	21	0	0
10	558853	8715404	1270	30	70	40	-159460.94	-6998.95	56.15	1.25	21	0	0
11	558861.6	8715399	1270	31	70	40	-159552.01	-7002.95	56.15	1.25	10.5	0	0
12	558870.3	8715394	1270	32	70	40	-133516.9	-5860.23	46.79	1.05	0	0	0
13	558852	8715463	1250	27	75	38	-238037.87	-10447.8	86.66	1.87	21	0	0
14	558911.6	8715486	1230	31	80	36	-292753.88	-12849.4	141.08	2.3	28.5	0.07	0
15	558837.7	8715598	1250	19	86	38	-184075.15	-8377.32	81.24	1.5	21	0.01	0.01
16	558862.4	8715561	1230	23	84	36	-289863.4	-12722.5	128.13	2.28	28.5	0.06	0
17	558845	8715571	1240	21	84	37	-226224.91	-12533.3	108.81	2.24	21	0.1	0.1
18	558848.7	8715557	1240	22	83	37	-288879.59	-12679.3	123.72	2.27	21	0.12	0

Figure 3.4: Block model prepared for import into SimSched

Each field related to economic value (Economic Value Process/Waste) must report the value of each block as a function of its destination, grades, recovery, cost of mining, transport, treatment and selling price. The following calculations show how the block value is calculated.

$$Block\ Tonnes = Block\ Volume * Block\ Density$$

$$Tonnes\ Cu = Block\ Tonnes * Grade\ Cu/100$$

$$Mass\ \text{Co} = Block\ Tonnes * Grade\ \text{Co}$$

$$\boldsymbol{Economic\ Value\ Process} = (Tonnes\ Cu * Recov\ Cu * (Selling\ Price\ Cu - Selling\ Cost\ Cu)) + (Mass\ \text{Co} * Recov\ \text{Co} * (Selling\ Price\ \text{Co} - Selling\ Cost\ \text{Co})) - (Block\ Tonnes * (Processing\ Cost + Mining\ Cost))$$

$$\boldsymbol{Economic\ Value\ Waste} = -\ Block\ Tonnes * Mining\ Cost$$

SimSched generates the volume report directly in Microsoft Excel and the optimised pit (blocks and surface) in SGeMS. Mined blocks can be exported to CSV in the block model folder. This model is usable in other software. Figure 3.5 shows a typical output from SGeMS, which is the graphical display of SimSched DBS.

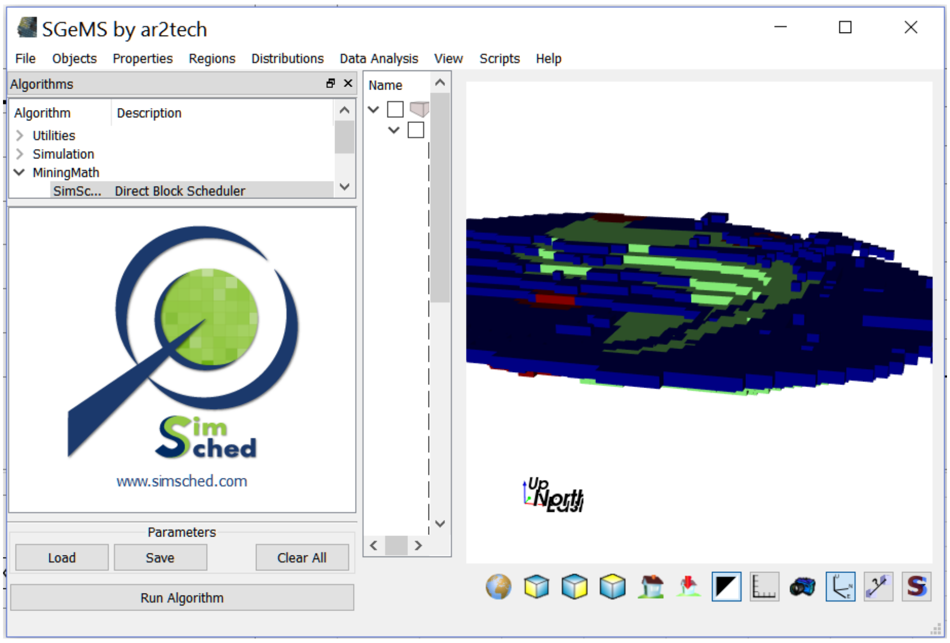


Figure 3.5: Typical SGeMS display showing schedule coloured by period

3.5.1 Preparation of the block model for use in SimSched DBS

The bench height for the Ruashi open pit is 5m. The block model has to be regularized to a 5 x 5 x 5 m blocks to conform to the mining configuration. Ruashi orebody consists of the oxide mineralisation at the top followed by a transition zone and lastly the sulphide This is shown in Figure 3.6. The current Ruashi refinery only processes oxide material. The cut-off grade optimisation therefore has to be conducted on the oxide and transition materials. Hence the sulphide mineralisation is flagged as waste in the model since it cannot be processed using the present set-up. The other parameters for calculating block economic value are also coded into the model.

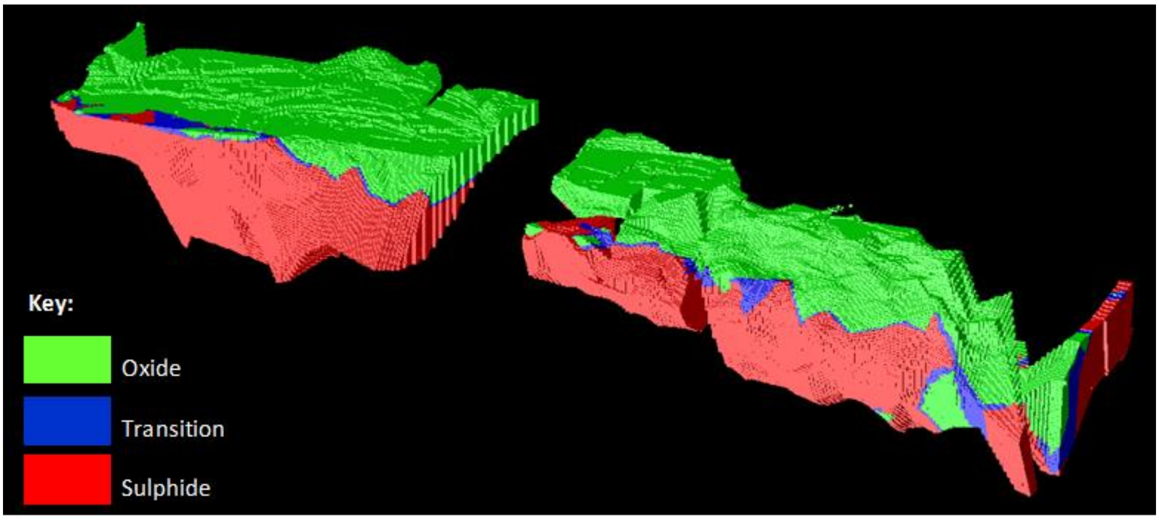


Figure 3.6: Ruashi orebody showing ore zones

It is important to restrict the schedule to the unmined part of the model. Hence the May 2016 survey month end topography is used to deplete the mined out part of the orebody. The model is then exported to csv for import into SimSched DBS.

3.6 Environmental costs consideration

Ruashi Mining carries out the waste dump rehabilitation concurrently with the mining. Once a dumping area is declared full, the rehabilitation process starts. This work is budgeted on an annual basis. It has been shown that delaying the waste dump rehabilitation increases the NPV and lowers the cut-off grade (Gholamnejad, 2008). Of the optimisation methods mentioned so far, only NPVS considers environmental costs. In order to investigate the impact of the waste dump rehabilitation to the cut-off grade, the environmental costs have to be extracted from the mining costs and the cut-off grade calculation redone per Gholamnejad (2008)'s findings.

3.7 Stockpiling and blending

Cut-off grade optimisation results in a declining feed grade policy if it is implemented (Dagdelen & Mohammed, 1997). Some operations like Ruashi Mining resorted to ore blending as a way of controlling some of the impurities in the ore but still maintain the required feed grade. This inevitably results in the mining of excess lower grade ore which has to be stockpiled for later processing. The stockpiled ore would then have to be re-handled when there is enough capacity in the processing plant. The re-handling involves equipment and labour which are costs. This implies that ore that is stockpiled must have higher grade than the break-even cut-off grade to cater for the re-handling costs.

SimSched DBS takes into account the costs of re-handling ore from the stockpile. Dagdelen and Mohammed (1997) give their findings on cut-off grade with and without stockpiling options. SimSched does not currently cater for processing of pre-existing stockpiles but NPVS does cater for pre-existing stockpiles. Only stockpiles that are generated during the execution of the schedule are processed..

3.8 Sensitivity and risk analysis

Input parameters are varied to investigate their effects on the NPV and cut-off grade. The major inputs to be varied include metal price, processing costs, discount rate and mining costs. Effects of rehabilitation costs are also demonstrated by incorporating rehabilitation costs in break-even cut-off grade.

@Risk software is used for risk analysis for optimisation results from SimSched. Probability distributions are assigned to the input parameters. These are then used instead of discrete values. The risk analysis results are then used to determine the parameters that have the greatest influence on the NPV. This will be shown on Tornado diagrams.

3.9 Chapter 3 summary

The chapter has given the selected methods that will be used in the research. The purposes of the inclusion of each of the methods has been given. It was also shown that three mining software will be used in order to compare results. The investigation of the effect of waste dump rehabilitation costs will also be done to show the effect on NPV and cut-off grade. @Risk software is used to conduct risk analysis.

CHAPTER 4: RUASHI MINING OPERATIONS OVERVIEW

4.1 Chapter overview

This chapter gives a brief overview of the Ruashi mining operations. The location of Ruashi in Katanga province of the Democratic Republic of Congo is given. A brief description of the regional and local geology is also given. The local stratigraphy and the Ruashi orebodies are shown. Ore minerals that make up the copper and cobalt mineralisation are described. The mining and processing operations overview is required for better understanding of the bottlenecks in the system.

4.2 Market overview

Copper is used in building, electronics, transportation and industrial machinery. It is also used in ‘green’ technologies such as solar cells and electric vehicles, and its antimicrobial properties are used to reduce the transfer of germs and disease. The price for copper has been decreasing over the past five years mainly due to the reduced Chinese demand given that the country consumed 40% of the world copper production. Figure 4.1 shows the five-year variation in the price of copper. The price of copper is however projected to rebound in the next three to four years (SRK Consulting, 2013).

Cobalt is used in the production of Ni-Cad batteries and as an alloy hardening agent for aircraft jet engines, gas turbines and coatings for other metal surfaces as well as diamond tools. Cobalt is used in pigmentations for glass and porcelain and as a supplement in animal feedstock. In organic derivative forms, it is used in paints and tyres. Radioactive ^{60}Co is used in the treatment of cancer. Cobalt is a component of vitamin B_{12}. The market for cobalt is poised for growth owing to its use in rechargeable batteries that are currently used in the production of hybrid electric vehicles (SRK Consulting, 2013).

Figure 4.1: Five-year copper spot price (KITCO, 2016)

4.3 Location, climate and infrastructure

The Ruashi Mine is located in the DRC, 10 km east of Lubumbashi, the capital city of Katanga Province. The mine is located in the peri-urban area to the northeast of Lubumbashi and on the outskirts of Ruashi Commune. The mine is located approximately 3.5 km southeast of the Lubumbashi International airport. The Congolese Copper belt is located in a sub-tropical zone characterised by distinct wet and dry seasons. Annual rainfall is approximately 1 200 mm and occurs during a wet season lasting from October to March with the heaviest rainfall occurring between December and March. Figure 4.2 shows the location of Ruashi Mining and other Metorex operations in the Democratic Republic of Congo.

Mining production is frequently impacted by the high rainfall as production from the open pits is stopped to allow haul ramps to dry. Key run-of-mine stockpiles and primary crushing installations are also impacted if material is too wet. Exploration drilling activities on the prospects are generally restricted to the dry season as vehicle access off the main bush tracks is not feasible during the wet season.

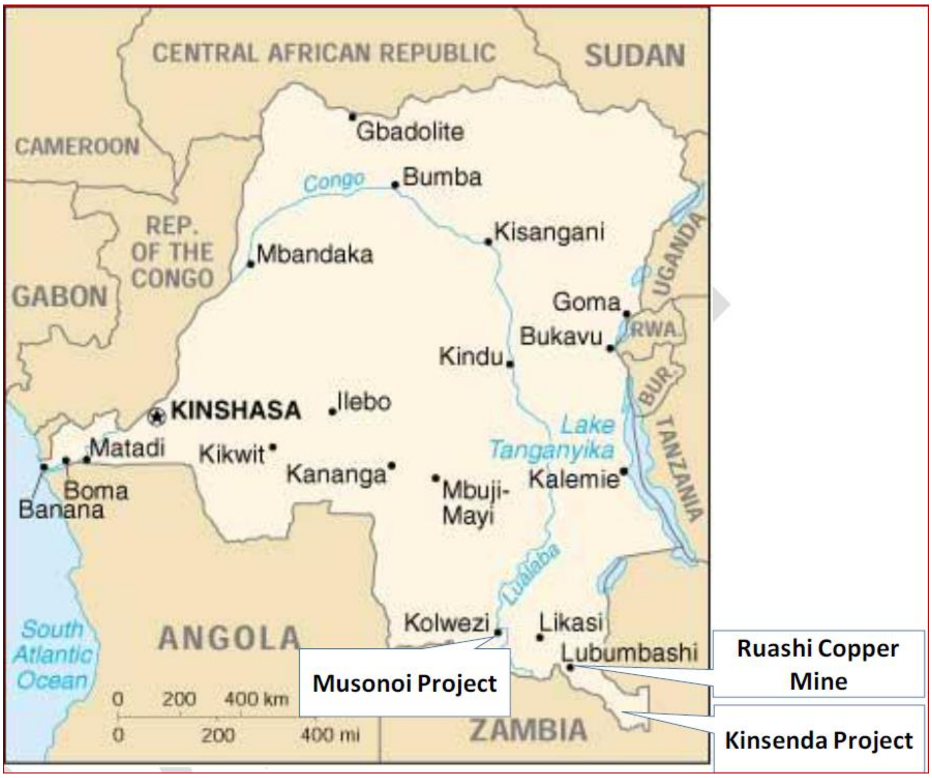


Figure 4.2: Location of Ruashi Mining and other Metorex projects (van Daalen, 2012)

The average air temperature remains fairly constant at between 17°C and 24°C throughout the year and there is no distinct winter and summer temperature regime. Average temperatures peak during September and October at 32°C. The coldest month is July with an average daily minimum of 6°C.

Water to the mine is supplied from underground aquifers. The geology is largely dolomitic and significant quantities of subsurface water are available. Return water from the tailings dam is also reused in the plant.

Power in the DRC is regulated and supplied by Société Nationale de Electricité ("SNEL"), the national power utility. The Ruashi Mine is fed at 220 kV (40 MW) by a dedicated power line. The mine has 13 diesel generators capable of producing 13 MW and a further 7 Caterpillar diesel generators, capable of producing 15 MW.

4.4 Geology

4.4.1 Regional geology

The Ruashi orebody is a stratiform, sediment-hosted copper deposit located in the Central African Copper belt which contains a third of the world's cobalt resources and a tenth of the world's copper reserves. The ore bodies are hosted by meta-sedimentary rocks of the Late Proterozoic Katangan System which is a 7 000m thick succession of minor volcanics, volcanoclastics and intrusives (Savage, 2014). The Katangan Sequence is divided into three Supergroups separated by two marker conglomerates as shown in Figure 4.3. The Kundelungu Supergroup was formed by detrital marine sediments which are predominantly dolomitic. Minor sandstone units are scattered throughout the succession. The Nguba (also known as Lower Kundelungu) was formed by detrital marine sediments which were predominantly dolomitic and is 3 000m thick.

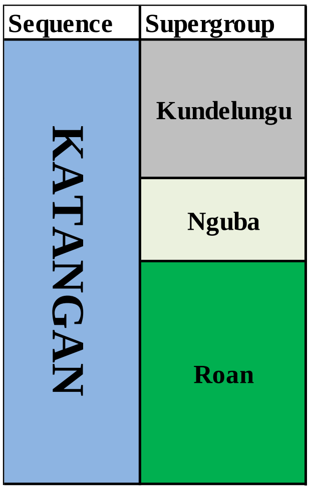


Figure 4.3: Litho-stratigraphic sequence of the Katangan Sequence in the Democratic Republic of Congo (Lubala, 2015)

The Roan Supergroup was formed by lagoonal and fluvial marine sediments consisting of dolostone, dolomitic siltstones and black shales with interstratified collapse breccias formed by the dissolution of evaporitic horizons with arkosic sandstones and conglomerate units. The thickness of the Roan Supergroup is 1 500m. The Roan Supergroup comprises the Roches Argileuses Talceuse (RAT), Mines, Dipeta and

Mwachya Group. The stratiform ores occur within two principal formations confined to a 40m thick succession at the base of the Mines Series. The upper formation comprises sandy shale, containing some carbonates. The lower formation consists of bedded dolomitic sandstone. The ore formations average approximately 10 m in thickness separated by 20m to 30m of siliceous dolomite. Ore grades commonly vary between 0% and 13% Cu and around 0.4%Co (Savage, 2014).

The weathered oxide zone generally extends to a depth of between 70 m and 150m, but may vary considerably between deposits. The weathering process commonly leads to high-grade supergene deposits near surface, but may also result in leaching of the mineralisation in places and/or concentration in otherwise barren horizons. At depth, a mixed oxide-sulphide zone grades into sulphide ore, sometimes at depths greater than 250m (SRK Consulting, 2013).

4.4.2 Ruashi local geology

Figure 4.4 shows the Ruashi local stratigraphy. Structurally, the Lower Roan fragments dip steeply to the north and strike in a NW-SE direction. The contacts with the Lower Kundelungu are brecciated. Three ore bodies have been identified within the Ruashi area: Ruashi I, Ruashi II and Ruashi III. Their relative positions are shown in Figure 4.5.

The Ruashi 1 orebody is the largest of the three ore bodies located in the extreme northwest of the area. The orebody is an overturned syncline formed by diapiric intrusion of RAT sediments into already existing large northwest-southeast trending fault zones. Downward leaching and subsequent erosion resulted in the mineralisation of the oxide minerals malachite and heterogenite in a near surface enriched zone in the form of a blanket zone overlying the orebody. However, the BOMZ-SDS oxide zone dips steeply at 70 degrees to the southwest. This oxide zone extends up to 300 meters below surface in the Pit 3 area. The lateral extent of the Pit 1 oxide orebody is about 900m in a NW-SE direction and 350m across strike. Sub-horizontal faulting has displaced the near surface part of the orebody to the NE.

SYSTEM	SERIES	FORMATION	LOCAL NAME	AGE		DESCRIPTION	THICKNESS
K	UPPER KUNDE-LUNGU					Sediments	30 - 50 m
			DIAMICTITE	570 ma		Glacial sediment, tillite	
A	LOWER KUNDE-LUNGU					Sediments Sandstones and shale	200 - 500 m
			DIAMICTITE	750 ma		Glacial sediment (Grand Conglomerate)	
T	R	R4 1 and 2	MWASHYA			Black Shales, siltstones, sandstones, dolomites	50 - 100 m
		R3 - 2	DIPETA			Shales, sandy schists	1000 m
		R3 - 1	RGS			Sandstones	100 - 200 m
A	O	R2 - 3	CMN			Talcose clays, sandy wad, dolomite	110m
			MIN CMN			Talcose clay and wad	0 - 20 m
		R2 - 2	BOMZ			Wad (manganeferous earth)	3 - 20 m
			SDS			Dolomitic shales, black graphitic shales	50 - 80 m
N	A	R2 - 1	SDB	U.O.B	COM-BINED ORE BODY	Basal dolomitic shales	10 - 15 m
			RSC	I. O. B		Stromatolitic dolomites	12 - 25 m
			RSF	LOWER ORE BODY		Foliated, silicious dolomites	5 m
G	N		D STRAT			Stratified, argillaceous dolomites	3 m
			MV			Massive green siltstone	2 - 10 m
		R1	RAT 2			Talcose argillites	100 m
A			RAT 1			Talcose argillites	40
			POUDINGUE	880 ma		Unknown transitional conglomerates	?
ARCHEAN BASEMENT				1870 ma 2050 ma		Volcano-sedimentary deposits Granite-gneiss	?

Figure 4.4: Ruashi local stratigraphy (Savage, 2014)

Figure 4.5: Satellite image of relative position of the three Ruashi ore bodies and pits (Google Maps, 2016)

The depth extent of significant primary sulphide mineralisation is 100 to 150 meters below surface. The orebody terminates against massive breccia in the west and a vertical faulting and sheared breccia in the east. The breccia is part of a major south dipping thrust fault.

Ruashi II is a smallest orebody extending along strike for about 300m and 250m across strike and the oxide orebody also terminates on strike against sheared breccia. A thick breccia zone separates Ruashi II from Ruashi I. The structural and weathering history of the orebody is similar to that of Ruashi I. Also, sub-horizontal faulting (breccia) has displaced the near surface part of the orebody 150 metres to the northeast. The geometry of the orebody below the breccia is now defined with borehole intersections. Significantly good sulphide mineralisation, especially in the RSC zone has been exposed. The bulk of the oxide part of Ruashi II has been depleted.

Ruashi III occurs at the south-easterly end of the strike and has a strike length of about 700m and extends across strike for 200m. The orebody occurs as an overturned syncline with less rotation compared to Ruashi I. It is overlain by a 20 to 50m thick ferruginous laterite. The orebody is terminated at a depth of 300m against a horizontal breccia. A deep weathering profile is present and the transition/sulphide boundary tends to conform to the lower portion of the orebody. The oxide ore has been indicated to extend to a depth of 300m. Primary sulphide mineralisation does occur within Ruashi III.

The major copper oxide minerals are malachite (copper carbonate), chrysocolla (hydrous copper silicate) and azurite (hydrous copper carbonate) in decreasing order of abundance. The major copper sulphide minerals are bornite (copper iron sulphide), chalcopyrite (copper iron sulphide) and chalcocite (copper sulphide). The major cobalt oxide minerals are heterogenite (hydrous cobalt oxide) cobaltocalcite (cobalt carbonate). The major cobalt sulphide mineral is carrolite (copper-cobalt-nickel sulphide). The transition between oxide and sulphide occurs over a distance of about 10m as observed in exposure in Pit 1.

4.5 Mining

The mining equipment is contractor owned and maintained by NB Mining. The mining is predominantly free dig of waste and ore by excavators. The ore is hauled to the designated stockpile area or run of mine pad and the waste is hauled to the designated waste dump. The mining fleet is shown in Table 4.1.

Table 4.1: NB Mining equipment fleet

Equipment	Type	Number	Remarks
Excavators	Hitachi ZX870L CR-3 3.6 m	4	In-Pit Ore & Waste Mining
Excavators	Hitachi X61200 6.5 m3	1	In-Pit Ore & Waste Mining
Excavators	Liebherr R974C HD	1	In-Pit Ore & Waste Mining
Excavators	CAT 374D	1	In-Pit Ore & Waste Mining
Dump Trucks	B40D 6x6 - 40t	7	In-Pit Ore & Waste Mining
Dump Trucks	B50D 6x6 - 50t	25	In-Pit Ore & Waste Mining
Back Hoe	Bell 315SJTurbo 4x4	1	In-Pit Ore & Waste Mining
Dozers	Cat D9R	6	Waste Dumps & In Pit
Dozers	Cat D8R	2	Waste Dumps & In Pit
Graders	Bell 770D	3	Haul Roads
Graders	Bell 872D	1	Haul Roads
Graders	Cat 140K	2	Haul Roads

4.6 Mineral processing

The Ruashi plant is a hydrometallurgical process which incorporates leaching, decantation, Solvent Extraction-Electrowinning (SX-EW) and cobalt purification and precipitation operations.

The Ruashi plant is a typical SX-EW plant. A simplified processing flow diagram is shown in Figure 4.6. Copper cathode is the main product with a cobalt carbonate produced as a by-product through precipitation. The plant was designed to treat 120 kilotonnes per month of feed ore and produce 3,800 tonnes per month copper cathode and 420 tonnes per month cobalt (contained in hydroxide).

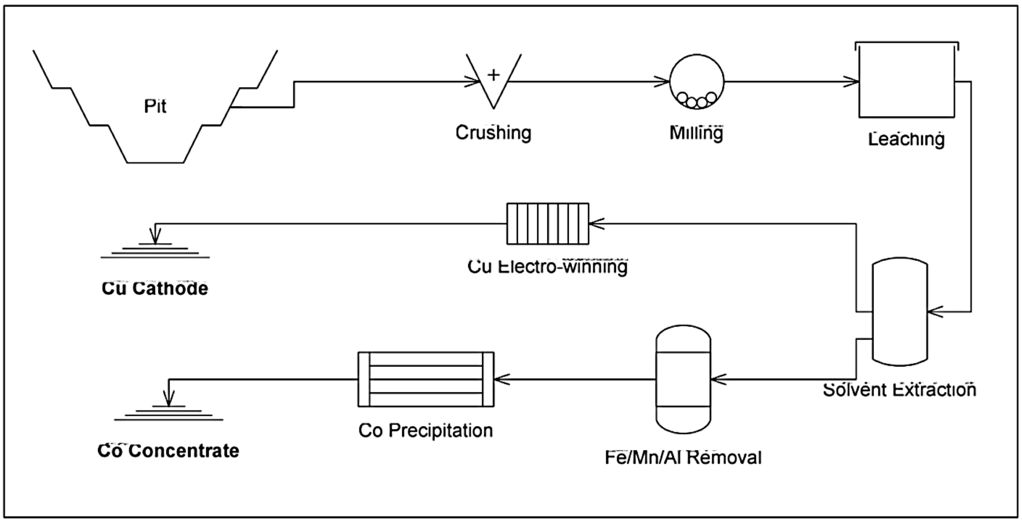


Figure 4.6: Simplified processing flow diagram, (van Daalen, 2012)

While each individual process has a capacity constraint based on one or more physical quantity or rate, the total process capacity is usually governed by one main bottleneck which is a capacity of 1,260,000 tonnes per annum. This is essentially a bottleneck in the leaching circuit, but measured in terms of mill feed tonnes.

4.7 Chapter 4 summary

The price of copper has been declining but is expected to rebound in the foreseeable future. Cobalt will soon be highly on demand for the manufacturing of rechargeable batteries. Ruashi is located in the Central African Copper Belt. There are three orebodies at Ruashi, namely Ruashi I, II and III. The oxide for Ruashi II has since been depleted. All the three orebodies comprise of oxide, transition and sulphide ore. The oxide is found at the top while the sulphide is found at depths. The transition zone between oxide and sulphide is approximately 10m.

Mining at Ruashi is carried out by a contractor who owns and maintains the mining equipment. The Ruashi plant is a typical hydrometallurgical plant which produces copper SX-EW processes. Cobalt is precipitated as cobalt hydroxide concentrates. The main bottleneck for Ruashi Mining is the mill which has an annual capacity of 1.26 million tonnes.

CHAPTER 5: RESULTS

5.1 Introduction

The chapter gives the analysis and comparison of results from the various optimisation processes that were carried out. The effect of royalty on Ruashi cut-off grade is also shown. The life of mine schedules for each of the scenarios are also given including the NPV and profit from each scenario. The scenarios investigated are, break-even cut-off grade, parametric, NPVS, SimSched and current MineSched life of mine cut-off grade policies. The main objective is to recommend a cut-off grade policy for Ruashi Mining that optimises the NPV.

5.2 Ruashi break-even cut-off grade

5.2.1 Input Parameters and Assumptions

The break-even cut-off grade refers to that grade at which revenue generated is equal to the production costs. Ore with grades higher than the break-even cut-off grade will generate more revenue than ore with grade below the cut-off grade. Hence, grades below the cut-off grade cannot pay for themselves. It is important to clarify costs that are used in break-even cut-off grade calculation and the objectives of using those costs should be stated (Hall, 2014). The parameters used in cut-off grade optimisation are given in Table 5.1.

Hall (2014) asserts that when the size of a pit has already been selected then the variable mining costs will be incurred for all the rock mined from the pit whether it is ore or waste. Open pit mining variable costs are therefore not included in ore – waste break-even distinction. This research is based on the Ruashi Mining 2013 pit designs. Hence there is no need to calculate the overall break-even cut-off grade at this point. Instead it is only necessary to calculate the marginal break-even cut-off grade based on the process which is the bottleneck in the Ruashi Mining production process. The mill is the bottleneck at present.

Table 5.1: Price and costs assumptions

Description	Symbol	Units	Value
Copper London Metal Exchange (LME) Price	pcu	$/t metal	6 200
Cobalt LMB Price	pco	$/lb metal	12.96
Copper Payability (% of LME Price)	mcu	%	100.00
Cobalt Payability (% of LMB Price)	mco	%	69.50
Royalty factor	r		0.9608
Mining cost	m	$/t mined	5.59
Processing cost	h	$/t milled	43.87
Element processing cost - copper	hcu	$/t copper contained in feed	671.35
Element processing cost - cobalt	hco	$/t cobalt contained in feed	3 802.89
Unit time costs	f	$/t milled	37.53
Selling cost per tonne copper	kcu	$/t metal sold	495.88
Selling cost per tonne copper	kco	$/t metal sold	2574.20
Discount rate	i	%	12.83
Copper recovery (Acid soluble copper AsCu)	y	%	95
Cobalt recovery (Acid soluble cobalt AsCo	y	%	85
Acid solubility	As	%	90
Grade acid soluble copper	AsCu	%	
Grade total copper	TCu	%	
Grade acid soluble cobalt	AsCo	%	
Grade total cobalt	TCo	%	
Dilution	d	%	

The Ruashi break-even cut-off grade for copper only (without considering cobalt credits) is calculated first using the following equation which does not take royalty into account:

COG = d*(h+f)/(y*(pcu – kcu) – hcu)

Where:

COG = cut-off grade

Therefore, for the given data and disregarding dilution because of the selective mining process:

COG = (43.87+37.53)/(95*(6200 – 495.88) – 671.35)

COG = 1.50% AsCu

COG (TCu) = 1.50/0.9

COG = 1.67% TCu

Ruashi Mining pays royalty to the government and to Gecamine, the mining company set up by the government to control the extraction of copper resources. The two add up to 3.93% of the revenue after the deduction of the transport, assay, insurance and marketing costs. Tax for corporations is pegged at 35% of net profit. However, mining companies are subject to a tax of 30% on net profits and not the 35%. Export of copper and cobalt concentrates was banned in 2013 to encourage mining companies to refine the metals locally before export.

It has been shown that royalty is a cost and has to be considered in the calculation of the cut-off grade (Birch, 2016). Therefore, the cut-off grade for copper is given by:

COG = d*(h + f)/(y(*pcu*r*mcu – kcu) – hcu)

This formula was incorporated into an Excel spreadsheet as shown in Table 5.2 to get the cut-off grade for copper.

Incorporating the royalty in the calculation of the break-even cut-off grade results in a 19.8% increase in the cut-off grade to 2.00 %TCu. This implies that royalty plays a significant role in determining the Ruashi cut-off grade and cannot be ignored because it has huge impact on profits. Hence the break-even cut-off grade for copper is 2.00 %TCu. The same formula was used to calculate the cut-off grade for cobalt assuming that the mine was a cobalt producing mine (that is ignoring the copper contribution).

Table 5.2: Figures for calculating break-even cut-off grade for copper

Parameter	**Units**	**Value**
Cu LME price	$/t	6,200
Royalty factor	-	0.96
Payability (% of LME)	-	1.00
Processing cost	$/t milled	43.87
Time cost - allocated to processing	$/t milled	37.53
Element processing cost	$/t metal contained in feed	671.35
Selling cost	$/t metal produced	495.88
Processing recovery	% of AsCu	95
Mining dilution	-	1.00
Processing cut-off grade	% AsCu	1.80
Ratio AsCu to Tcu		0.90
Processing cut-off grade	% TCu	2.00

This formula was again incorporated into an Excel spreadsheet as shown in Table 5.3 below.

$$COG = d*(h + f)/(y(*pco*r*mco – kco) – hco)$$

The cobalt is a by-product in the copper production process. The break-even cut-off grade for copper must therefore include the contribution of cobalt to the revenue. This means there is a combination of copper and cobalt grades which make the company make no profit. This is illustrated in Figure 5.1. A line joining the copper and cobalt break-even cut-off grades is the distinction between ore and waste as shown in Figure 5.1. Material with combined grades above the line will be processed while that below will be discarded as waste. The diagram shows that material with copper grades which are less than 2.00%TCu can still be treated as long as the corresponding grade of cobalt makes the material fall above the line. This is caused by the contribution of cobalt to the revenue.

Table 5.3: Figures for calculating break-even cut-off grade for cobalt

Parameter	**Units**	**2016 Value**
Co LMB price	$/lb	12.96
Royalty factor	-	0.96
Payability (% of LMB)	-	0.70
Processing cost	$/t milled	43.87
Time cost - allocated to processing	$/t milled	37.53
Element processing cost	$/t metal contained in feed	3,803
Selling cost	$/t metal produced	2,574.20
Processing recovery	% of AsCo	0.85
Mining dilution	-	1.00
Processing cut-off grade	% AsCo	0.80
Processing cut-off grade	% TCo	0.88

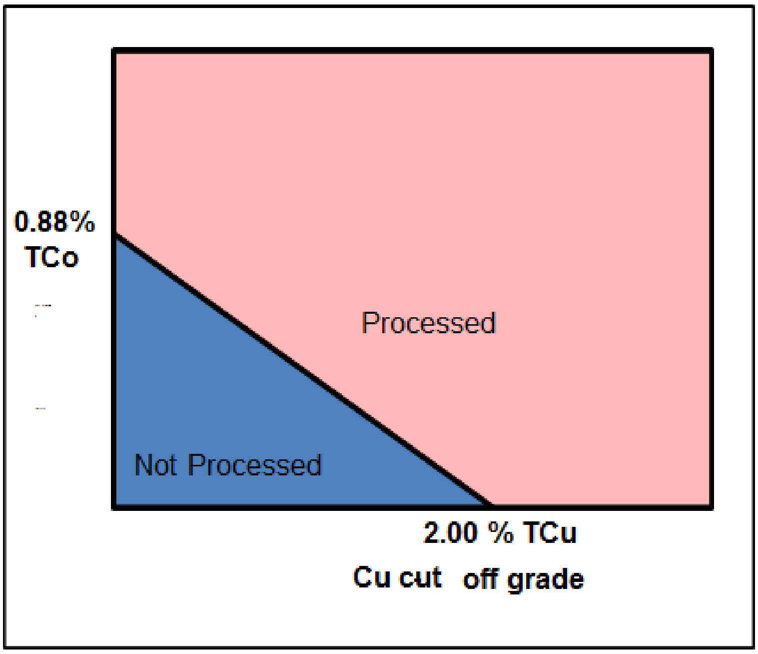


Figure 5.1: Relationship between copper and cobalt cut-off grades (van Daalen, 2012)

Figure 5.2 shows that about 30 million tonnes of the material has grades below 1.00%TCu, which is about 81% of the mineralised material. The Ruashi deposit grades are skewed towards the lower grades because the tonnage graph in Figure 5.2 is steeper at the beginning and then flattens gradually. This means that the bulk of the tonnage is in the low grade range. This is why a small change in cut-off grade results in a huge change in tonnage. For example, the change from the current break-even cut-off grade of 0.9%TCu applied at the mine to 2.0%TCu calculated above has resulted in a loss of 2.7 million tonnes of ore from the reserves.

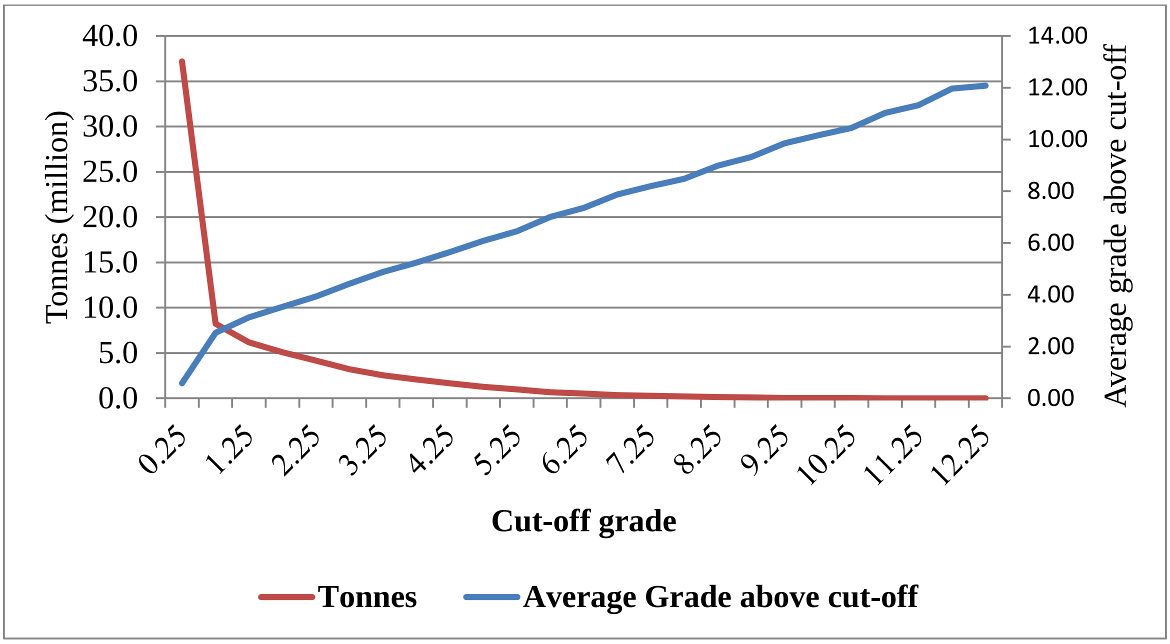


Figure 5.2: Grade-tonnage curves for copper (%TCu)

The grade distribution for cobalt mineralisation follows a similar trend to that of copper even though there is no correlation between the two. Figure 5.3 shows the tonnage-grade curves for cobalt.

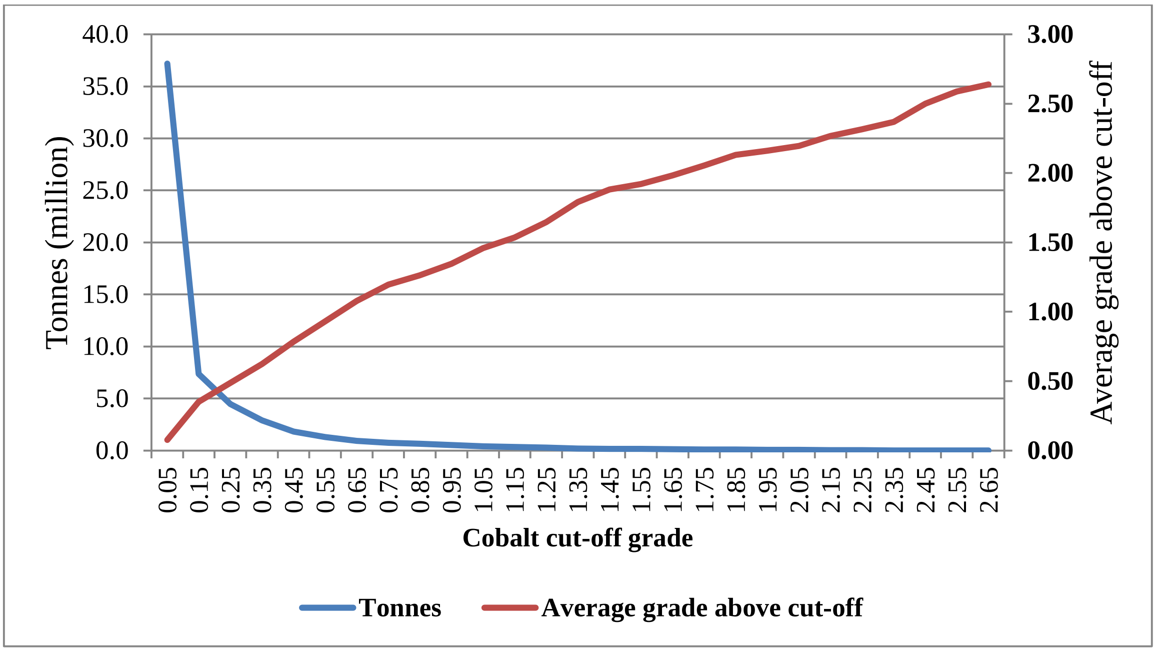


Figure 5.3: Grade-tonnage curves for cobalt

The curves are very steep for grades in the lower grade range. Since the biggest amount of material is concentrated closer to zero, a small change in the cut-off grade caused by a change in either the price or the costs has a significant impact on the reserves and hence on the life of mine.

5.2.2 Life of mine cash flow based on break-even cut-off grade

Table 5.4 shows the profit and NPV generated for the life of mine based on the break-even cut-off grade of 2.00%TCu calculated in Section 5.2.1.

Table 5.4: Life of mine schedule based on break-even cut-off grade

Year	Mined Tonnes	Processing	COG	Average Grades		Cu Cathode	Co in Conc	Profit	NPV
	(Mtonnes)	(Tonnes)	%TCu	%TCu	%TCo	(Tonnes)	(Tonnes)	($m)	($m)
1	10.74	1.2	2.00	3.75	0.26	38,274	2,059	79.33	70.31
2	10.74	1.2	2.00	3.75	0.26	38,274	2,059	79.33	62.32
3	10.74	1.2	2.00	3.75	0.26	38,274	2,059	79.33	55.23
4	2.41	0.3	2.00	3.75	0.26	8,597	462	17.82	10.99
Total	**34.62**	**3.87**		**3.75**	**0.26**	**123,419**	**6,638**	**255.82**	**198.85**

The cobalt cut-off grade is not considered in this case because it is only a by-product. However, its contribution to the revenue is taken into account by including cobalt credits in the calculation of the copper cut-off grade. The effect of this is to lower the variable production costs with the credits received from the cobalt by-product. All the costs from mining to solvent extraction are allocated to copper (Figure 4.6). Cobalt is only allocated those costs directly related to it like the element processing cost, cobalt selling costs and royalty. These have to be deducted from the cobalt revenue (price) per tonne.

If one merely looks at an average feed grade of 3.75%TCu, it is easy to be inclined towards thinking that this method is perfect. It is however important to recall that the break-even grade is based on financial parameters only which are adjusted for metallurgical recoveries. It does not take into account the spatial distribution of the grades in the orebody. In practice the grades would vary either above or below the average grade. This is not good for the plant because the spikes in feed grade would negatively affect the metal recoveries and hence the revenue. Therefore, the predicted NPV might not be achievable.

The break-even cut-off grade does not provide for capital payback because it makes no provision for profit. Investments are made in order to primarily grow the wealth of shareholders and yet the break-even grade does not provide for this. The grade distribution of the Ruashi orebody is skewed towards the low grade portion as shown in Figure 5.2. As such, the cut-off grade calculated cuts out most of the lower grade portion of the material. This drastically reduces the mineral reserves.

5.3 Cut-off grade optimisation in NPVS

5.3.1 Parameters and Assumptions

The financial parameters used in this cut-off grade optimisation are shown in Table 5.. As in all other scenarios, sulphide mineralisation was flagged as waste in the model to ensure that the optimisation was only run on oxide mineralisation. The Ruashi Base Metal Refinery (BMR) is only designed to treat oxide ore. The NPVS adopts a declining cut-off grade given by the following equation:

$$\mathbf{COG = (h + (hcu + F)/H)/((pcu - kcu)*y)}$$

Where:

F = opportunity cost ($ per annum)

H = mill capacity (tonnes per annum)

The rest of the symbols are as defined in Table 5.1.

The scheduler was set up to run in quarters of a year, so the necessary adjustments were made to the parameters. This was done to make the results clearer since the mine has a short life.

5.3.2 Optimisation results

Table 5.5 shows the results from the NPVS. Copper grades are around 2% or above. This is mainly due to the fact that NPVS considers the contribution of both metals in the optimisation process. The life of mine schedule from NPVS favours the declining cut-off grade strategy. Figure 5.4 shows the declining copper grades over the life of mine.

Table 5.5: Life of mine schedule from NPVS

Year	Rock	Mill_Feed	%TCu	%TCo	Cu_Cathode	Cobalt_R	Strip
1	3,299,035	1,260,749	3.14	0.24	31,987	1,852	1.6
2	2,098,831	1,260,603	2.71	0.21	27,608	1,662	0.7
3	3,273,019	1,259,433	2.30	0.31	23,394	2,443	1.6
4	3,617,355	1,259,926	2.39	0.36	24,288	2,801	1.9
5	2,018,975	1,259,325	2.26	0.40	23,004	3,075	0.6
6	787,375	653,749	2.12	0.20	11,184	798	0.2
Total	**15,094,590**	**6,953,785**	**2.52**	**0.29**	**141,465**	**12,632**	**1.2**

The copper average grade starts low in the first quarter because of the unavailability of enough exposed high grade ore due to waste stripping backlog, rises in the second and then declines gradually over the life of mine. The stripping ratio shown in Table 5.5 is high at the beginning due to accelerated waste stripping in order to expose high grade ore, then drops in order to minimise cash outflow to increase the NPV. It then starts increasing gradually.

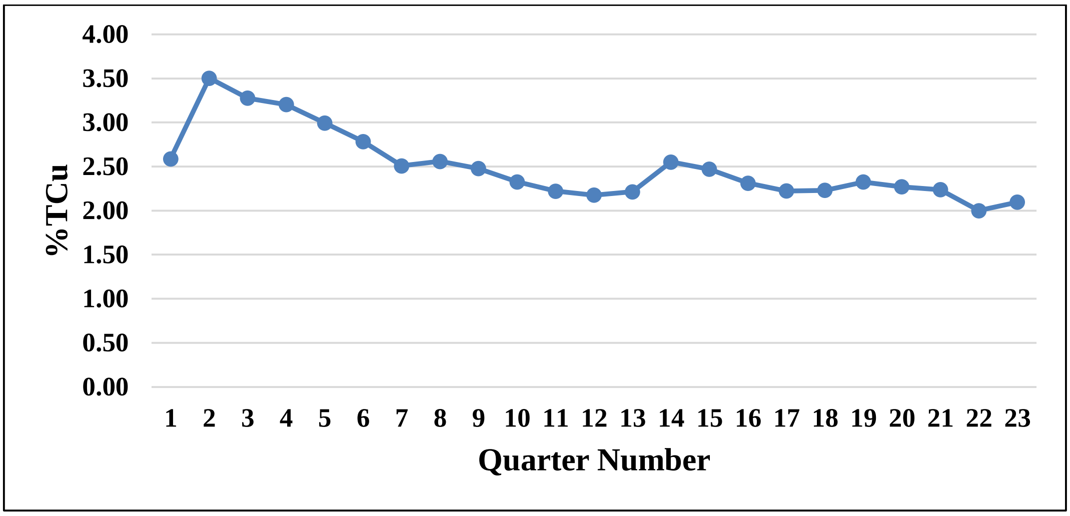


Figure 5.4: Variation of copper grades over the life of mine

The copper grade is generally high at the beginning of the life of mine and then decreases gradually until the end of the life of mine. The cobalt grade is not showing any trend because cobalt is a by-product in the process. It was not targeted in the optimisation process but was included as a source of additional revenue. Figure 5.5 shows the variation of the cobalt grade over the life of mine. The cobalt grades start up low and then increase towards the end of life and then revert to the downward trend. This is caused by the nature of mineralisation. In most cases blocks with high cobalt content contain less or no copper at all. The aim is to optimise copper output because it is the major source of revenue. So trying to increase the grade of cobalt in the blend has a dilution effect on the copper grade. The schedule therefore favours those blocks which contain both copper and cobalt even if cobalt is at a lower grade.

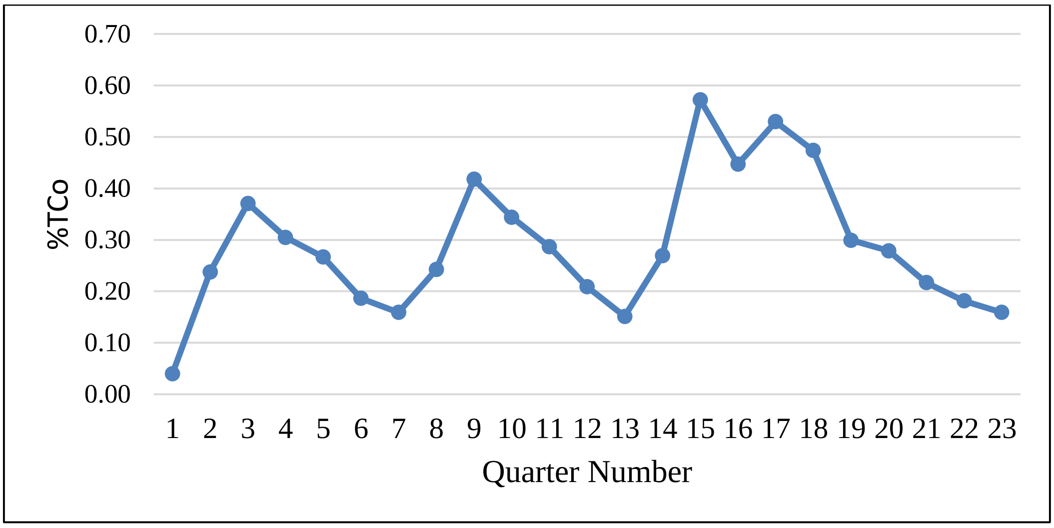


Figure 5.5: Variation of cobalt grades over the life of mine

The metal outputs follow the same distribution as the grades over the life of mine. Figure 5.6 shows the copper and cobalt output over the life of mine.

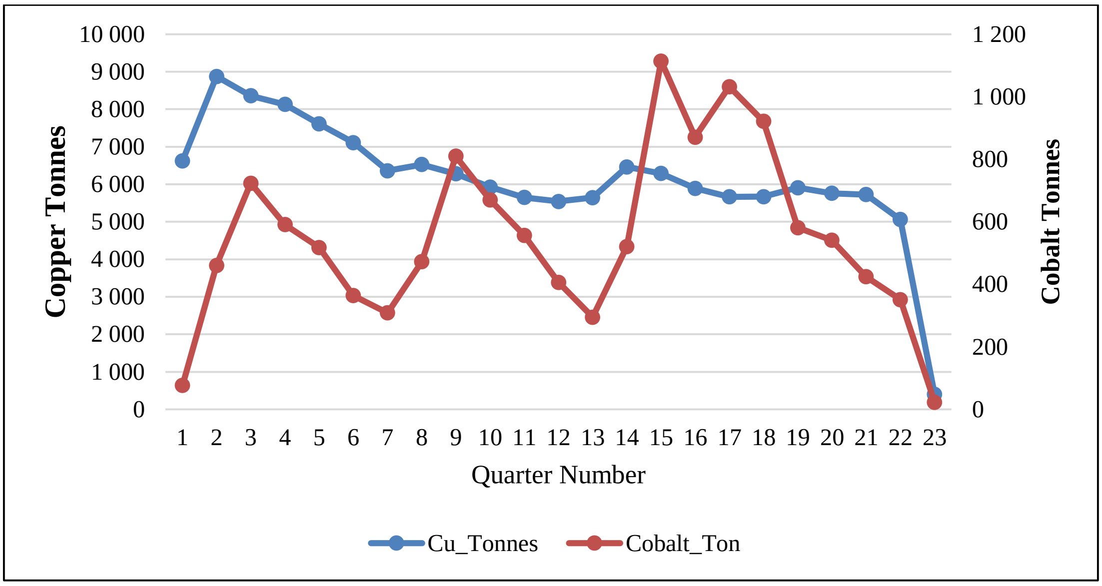


Figure 5.6: Life of mine metal output

The decline in metal output in the first quarter is quite evident. As mentioned earlier, this is caused by the waste stripping backlog which accumulated over the previous years. The cobalt production is not optimised because the main focus is on copper output which is the main source of revenue. Cobalt output follows an opposite trend to that of copper. Cobalt production is maximised (automatically) when the copper is getting depleted. Maximisation of copper grades tends to displace cobalt from the feed, hence the increase in cobalt output after the depletion of copper.

Figure 5.7 shows the life of mine NPV. The low NPV is evident in the first quarter. It can however be seen that the NPV is highest at the beginning of the life of mine which is in line with the objective of cut-off grade optimisation.

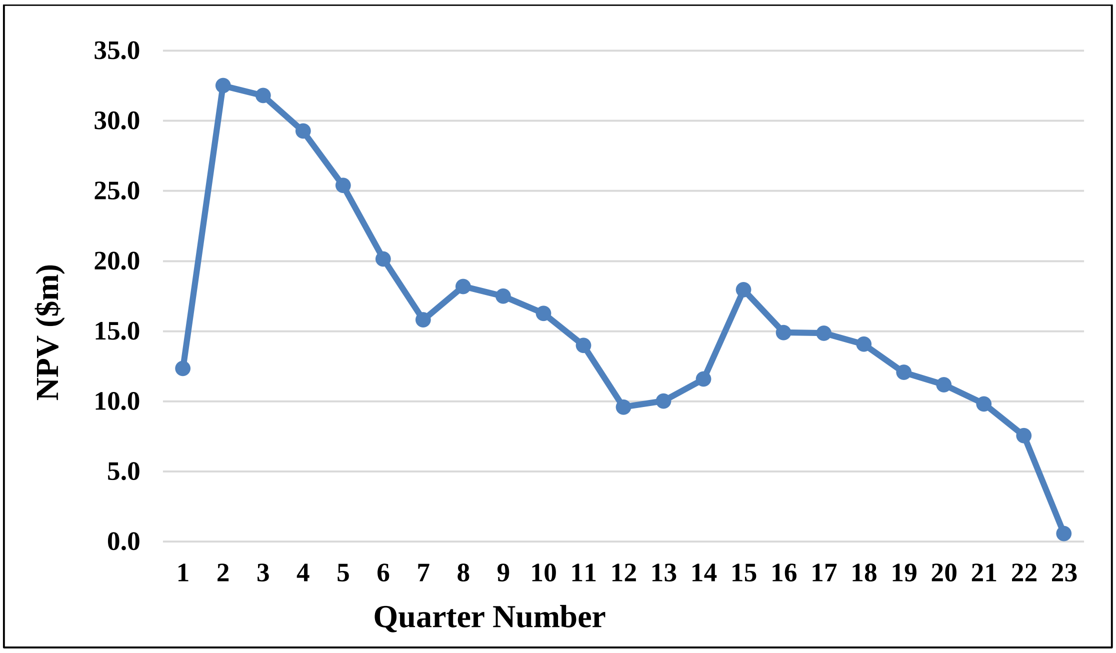


Figure 5.7: Life of mine NPV

The life of mine is about 5.8 years. Schedule optimisation in NPV does not lead to high-grading. Figure 5.8 shows the cumulative NPV for the life of mine.

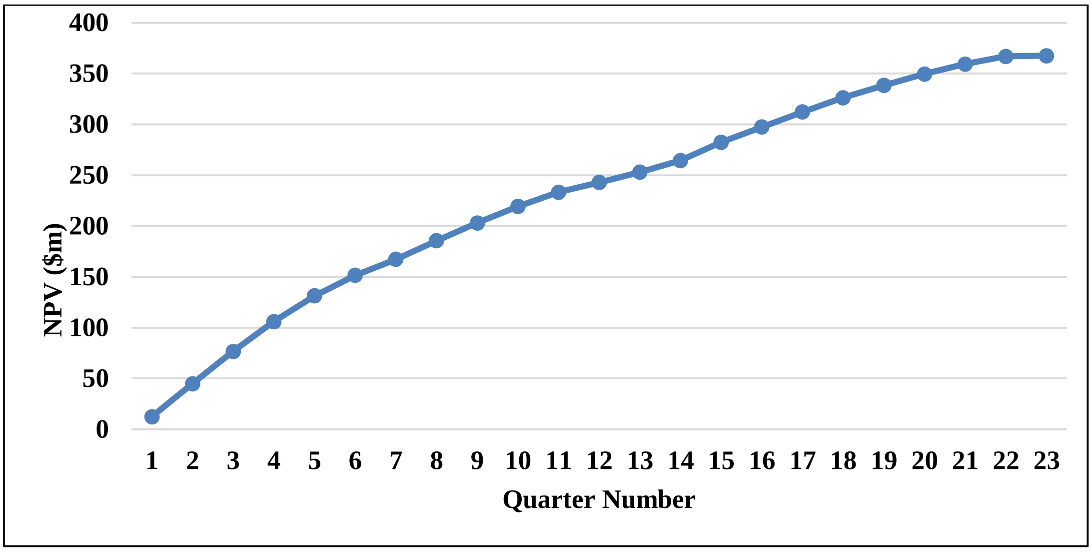


Figure 5.8: Life of mine cumulative NPV

The cumulative NPV increases steadily over the life of mine as one might expect. The curve almost flattens at the end of the mine life.

Table 5.6: Life of mine schedule based on NPVS

Year	Mined Tonnes (Mtonnes)	Processing (MTonnes)	Optimum Grades %TCu	%TCo	Cu Cathode (t)	Co in Conc (t)	Profit ($m)	NPV ($m)
1	3.30	1.3	3.14	0.24	33,671	1,950	88.83	78.72
2	2.10	1.3	2.71	0.21	29,061	1,750	74.92	58.85
3	3.27	1.3	2.30	0.31	24,625	2,571	61.93	43.11
4	3.62	1.3	2.39	0.36	25,565	2,948	67.50	41.65
5	2.02	1.3	2.26	0.40	24,215	3,237	71.56	39.13
6	0.79	0.7	2.12	0.20	11,772	841	27.43	13.30
Total	**15.09**	**6.95**	**2.52**	**0.29**	**148,909**	**13,297**	**392.16**	**274.77**

The NPVS gives a lower average grade for the reserves but the tonnage is higher than that produced by the break-even analysis. The NPVS follows the declining cut-off grade policy as shown in Table 5.6. Material is scheduled in such a way that the low grade ore which is processed at the end of the mine life still remains economic to process.

5.4 Optimisation based on recoverable value (SimSched DBS)

5.4.1 Parameters and Assumptions

The parameters are as shown in Table 5.. The setup for scheduling in SimSched DBS is shown in Figures 5.9 and 5.10.

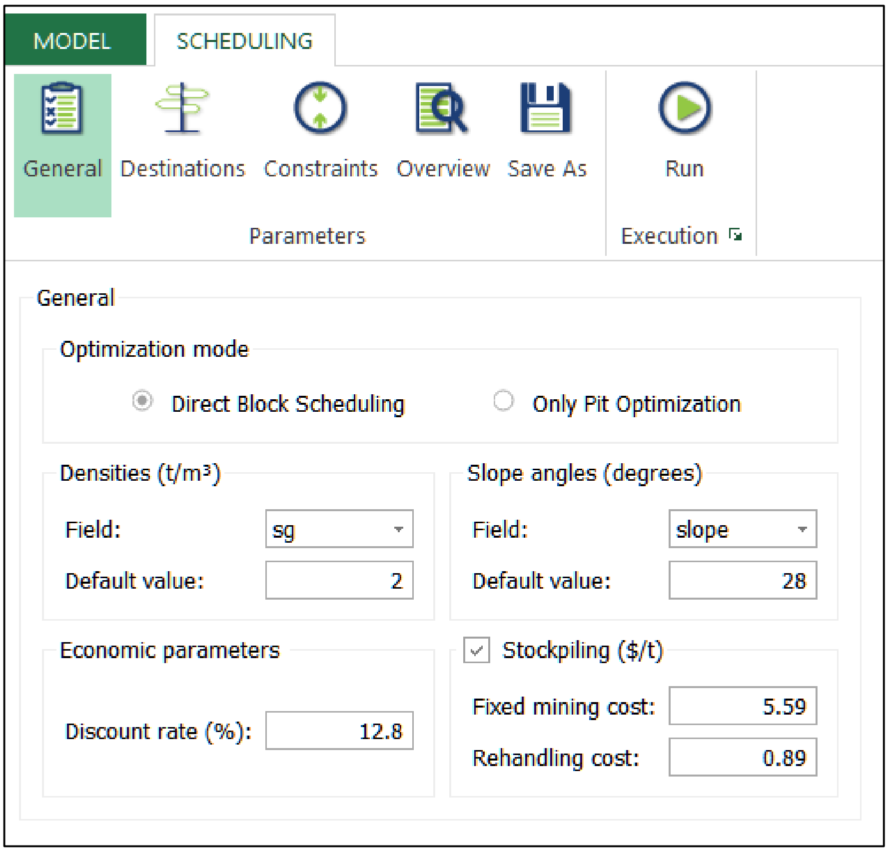


Figure 5.9: SimSched DBS setup

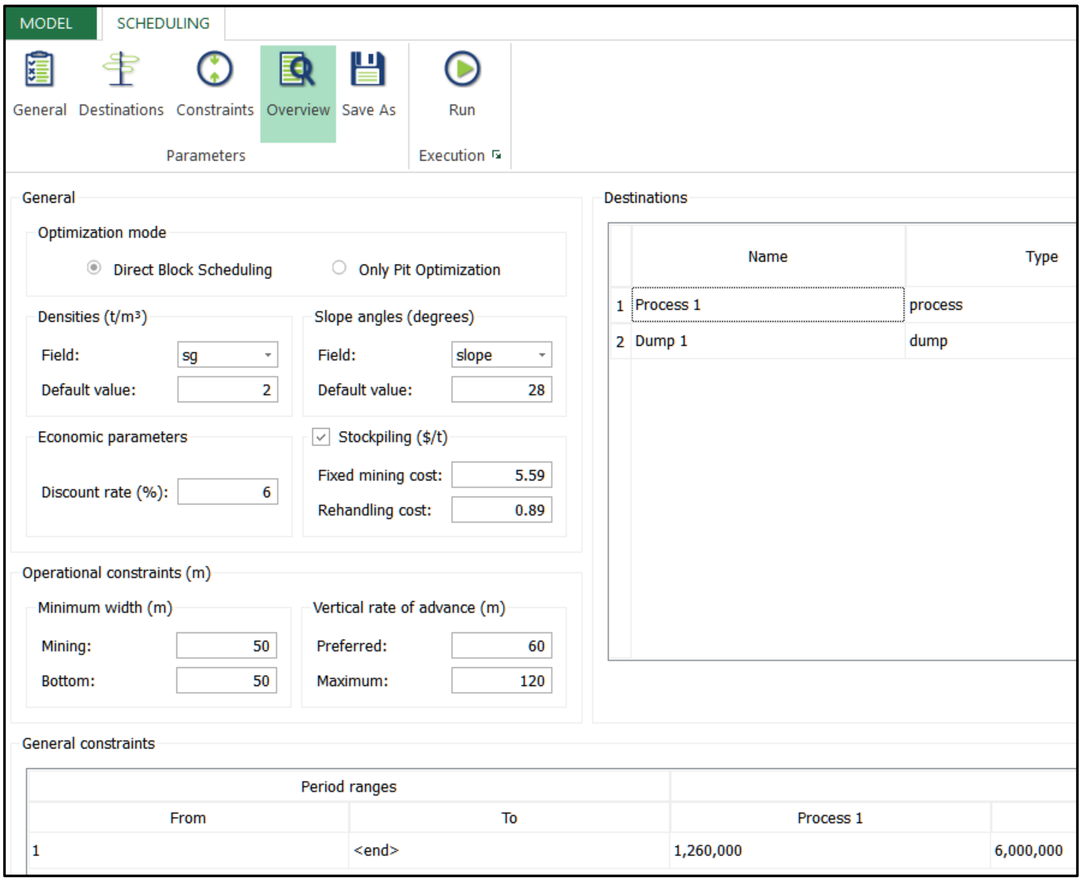


Figure 5.10: Overview of SimSched setup

5.4.2 SimSched DBS Optimisation results

The mill feed tonnes are achieved for six years. However, the feed grade becomes too low to a level which might render the recovery of the metal uneconomic. The results are shown in Table 5.7.

Table 5.7: SimSched DBS life of mine schedule

Period	Waste Mined (kt)	Tonnes Processed (kt)	Feed Grades %TCu	Feed Grades %TCo	Copper Produced (kt)	Cobalt Produced (kt)
1	6,734.6	1,258.1	4.07	0.23	43.5	1.86
2	6,731.1	1,264.5	3.08	0.46	33.1	3.74
3	7,339.0	1,264.0	3.00	0.24	32.2	1.95
4		1,248.8	1.75	0.25	18.5	2.05
5		1,249.3	1.08	0.27	11.5	2.21
6		1,248.0	0.80	0.20	8.5	1.59
Total	**20,804.7**	**7,532.6**	**2.30**	**0.27**	**147.2**	**13.4**

However, the treatment of lower grade ore from Year 5 onwards is not economic because the grades are low and metal output is also low. SimSched DBS shows positive NPV as shown in Figure 5.11. The mill capacity is fully utilised with low grade ore. The recovery at such low grades might not be high enough to extract the metal. Further studies are required to investigate the effect of feed grade on metal recovery.

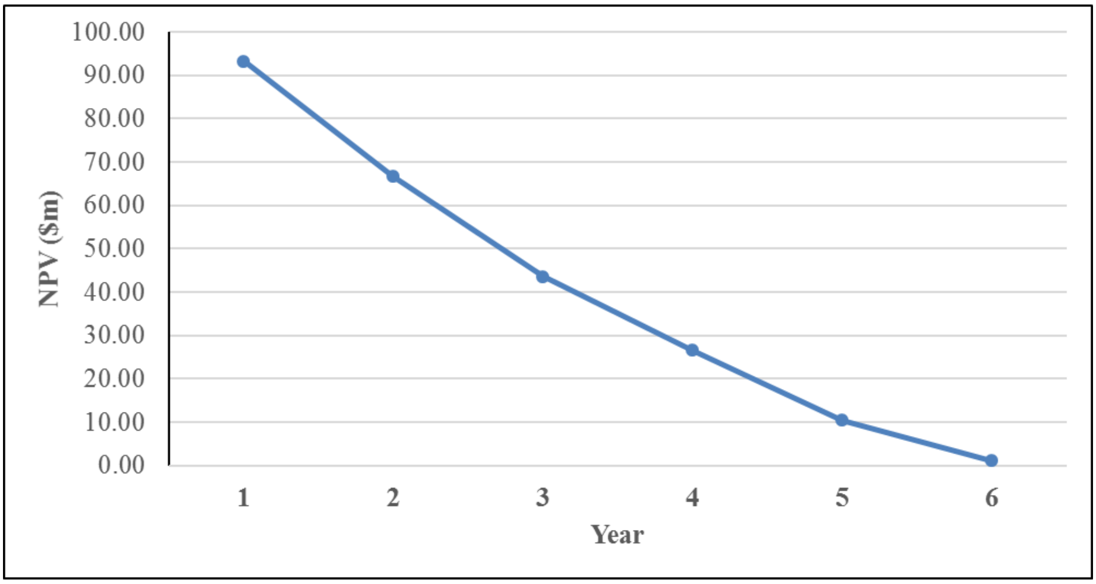


Figure 5.11: Variation of NPV over the life of mine

The schedule suggested in Table 5.7 requires massive stockpiling of low grade ore for processing later as shown in the stockpile schedule in Table 5.8.

Table 5.8: Stockpile schedule from SimSched DBS

Year	Added to stockpile (Mt)	Removed from stockpile (Mt)	Stockpile balance (Mt)
1	3.2	1.2	1.9
2	3.7	1.2	4.4
3	0.6	1.2	3.8
4	-	1.2	2.5
5	-	1.2	1.3
6	-	1.2	0.0
Total	**7.5**	**7.5**	

The stockpile schedule is also given in Figure 5.12.

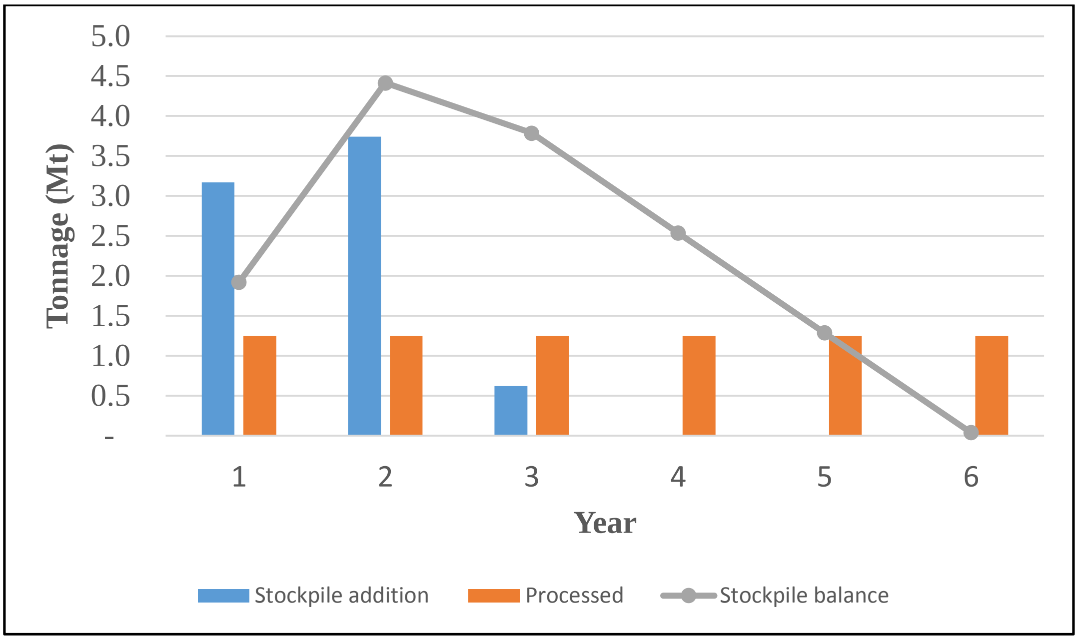


Figure 5.12: Stockpile schedule from SimSched DBS

The life of mine grades are generally high whilst there is still production from the pit. Once ore from the pit is depleted and stockpile reclamation starts, the grades also begin to drop. Figure 5.13 shows the variation of the cobalt feed grade over the life of mine and Figure 5.14 shows the corresponding grades for copper. Both copper and cobalt generally follow the declining cut-off grade trend.

SimSched DBS optimises the net smelter return, which is depicted by the block economic values in the block model. In the first year, the value is optimised by scheduling the optimum grade of copper. In the second year the available blocks have lower copper grade, which results in a decline in net smelter return. This gap in net smelter return is addressed by optimising the grade of available cobalt. As a result the grade of cobalt in the second year increases to the maximum available. In subsequent years higher grade material for both copper and cobalt is depleted and hence feed grades for both decline.

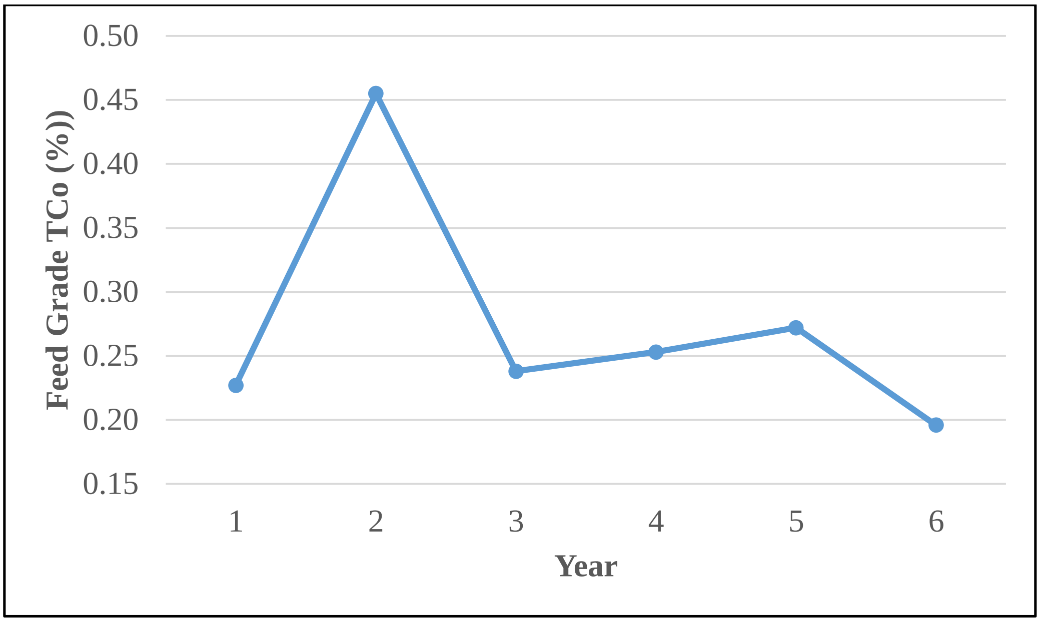


Figure 5.13: Variation of cobalt feed grade over the life of mine

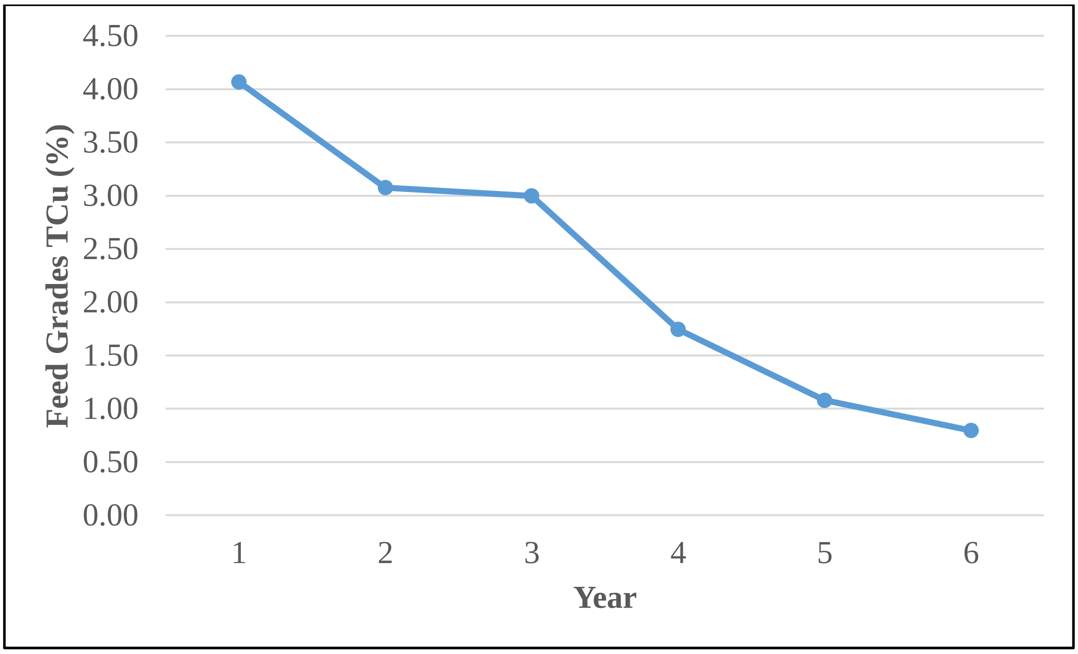


Figure 5.14: Variation of copper grade over the life of mine

SimSched DBS optimises the NPV by optimising the schedule based on block value. The block values are skewed towards the cobalt production due to the higher price of cobalt hence the processing of marginally low copper grades which might not be practical to process since they might not be leachable. There is a sharp increase in the NPV in the first three years of the life of mine. Thereafter it tails off due to the depletion of high grade ore. The life of the mine is short and hence the schedule is similar to high-grading. This is evidenced by such a high stockpiling of low grade material in just three years of mining. Figure 5.15 shows the cumulative NPV over the life of the operation. The NPV follows the same trend as that produced by NPVS in Figure 5.8. The different timescales somewhat distorts the cumulative NPV shown in Figure 5.8.

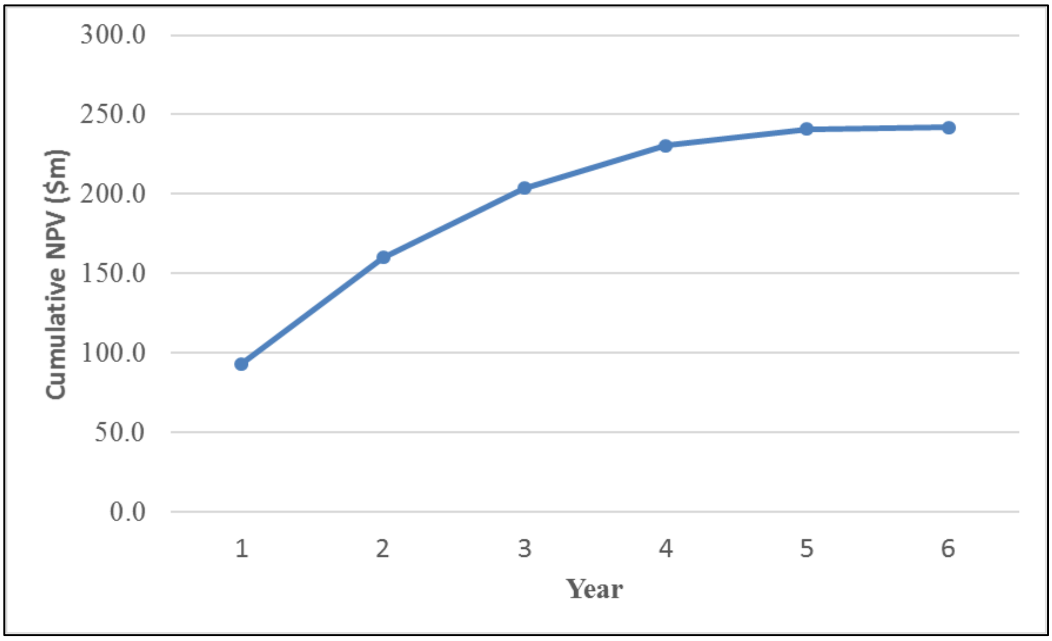


Figure 5.15: SimSched DBS cumulative life of mine NPV

As mentioned above, the practical life of mine from this schedule is approximately six years. SimSched DBS processes 8.4% more ore compared to the NPS. Table 5.9 shows the life of mine production schedule from SimSched DBS.

Table 5.9: The practical life of mine schedule extracted from SimSched

Period Years	Waste Mined (kt)	Tonnes Processed (kt)	Feed Grades %TCu	Feed Grades %TCo	Copper Produced (kt)	Cobalt Produced (kt)
1	6,734.6	1,258.1	4.07	0.23	43.5	1.86
2	6,731.1	1,264.5	3.08	0.46	33.1	3.74
3	7,339.0	1,264.0	3.00	0.24	32.2	1.95
4		1,248.8	1.75	0.25	18.5	2.05
5		1,249.3	1.08	0.27	11.5	2.21
6		1,248.0	0.80	0.20	8.5	1.59
Total	20,804.7	7,532.6	2.30	0.27	147.2	13.4

Economic metal output is only achieved in the 3 out of the 6 years. Table 5.10 shows the life of mine NPV.

Table 5.10: Life of mine cash flow based on SimSched DBS schedule

Year	Mined Tonnes (Mtonnes)	Processing (MTonnes)	Optimum Grades %TCu	Optimum Grades %TCo	Cu Cathode Tonnes	Co in Conc Tonnes	Profit ($m)	NPV ($m)
1	7.99	1.26	4.07	0.23	43,490	1,856	105.33	93.35
2	8.00	1.26	3.08	0.46	33,062	3,740	84.84	66.64
3	8.60	1.26	3.00	0.24	32,209	1,955	62.73	43.67
4	1.25	1.25	1.75	0.25	18,523	2,054	43.19	26.65
5	1.25	1.25	1.08	0.27	11,469	2,209	19.01	10.39
6	1.25	1.25	0.80	0.20	8,455	1,590	2.33	1.13
Total	**28.34**	**7.53**	**2.30**	**0.27**	**147,208**	**13,404**	**317.41**	**241.83**

The mine makes profit for six years and the profit is at its maximum in the first year in line with the goal of cut-off grade optimisation. The feed grade is highest at the beginning and declines over the life of mine. SimSched DBS does not carry out optimisation based directly on grades, but the recoverable value of each block. It is apparent that the software follows a declining cut-off grade policy. It is also evident that even though the optimisation is based on the recoverable value, the copper grades are indeed optimised.

5.5 Parametric cut-off grade

5.5.1 Parameters and assumptions

The conversion to copper equivalent for a block is based on the following equation:

$$\text{Copper Equivalent Grade} = \text{TCu} + \frac{\text{TCo} * (\text{y} * (\text{pco} - \text{kco}) - \text{hco})}{\text{y} * (\text{pcu} - \text{kcu}) - \text{hcu}}$$

The symbols are as given in Table 5..

This formula was incorporated into the block model and the model depleted with the May 2016 Survey month end measurement. The resulting model was then exported to csv format for use in SimSched DBS. The other financial parameters were assumed to be those for copper.

5.5.2 Optimisation results

Table 5.11 shows the scheduling results from SimSched.

Table 5.11: Life of mine schedule based on parametric cut-off grade

Period	Mined (Mt)	Processed (kt)	Optimum Grade (% Copper Equivalent)	Metal Output (kt)
1	7.76	1,261.5	4.70	50.43
2	6.67	1,264.3	3.21	34.49
3	9.99	1,264.2	3.78	40.57
4	1.25	1,248.2	2.29	24.32
5	1.25	1,247.4	1.55	16.47
6	1.25	1,248.3	1.14	12.14
Total	28.17	7,534.0	2.79	178.42

The copper equivalent optimised grade follows the declining cut-off grade in the life of mine, which results in higher metal output in the first three years. This is also in line with the cut-off grade optimisation objective of optimising the value of the mine. The optimisation results in accelerated mining and massive stockpiling. The stockpiling process is shown in Table 5.12.

Table 5.12: Stockpile schedule based on parametric cut-off grade

Period	Addition (Mt)	Depletion (Mt)	Balance (Mt)
1	4.72	0.00	4.72
2	1.90	0.00	6.62
3	1.70	0.00	8.32
4		1.25	7.07
5		1.25	5.83
6		1.25	4.58

Table 5.12 shows that a whopping 8.3 million tonnes is stockpiled in the first three years of the life of mine. This ties up a lot of capital in the ore on the stockpiles. This is due to the policy to accelerate the mining rate to get the higher grade ore for NPV optimisation. About 4.6 million tonnes remain on the stockpile because it becomes uneconomic to process that material at such low grades. The mill throughput is fully utilised but with very low metal output. Figure 5.16 shows the stockpile schedule. Because of the requirement to optimise value, the stripping is accelerated to expose the high value blocks.

The depletion of ore from the stockpiles only starts when the mining from the pit is exhausted. This also marks the beginning of the decline in grade and hence a corresponding decline in metal output.

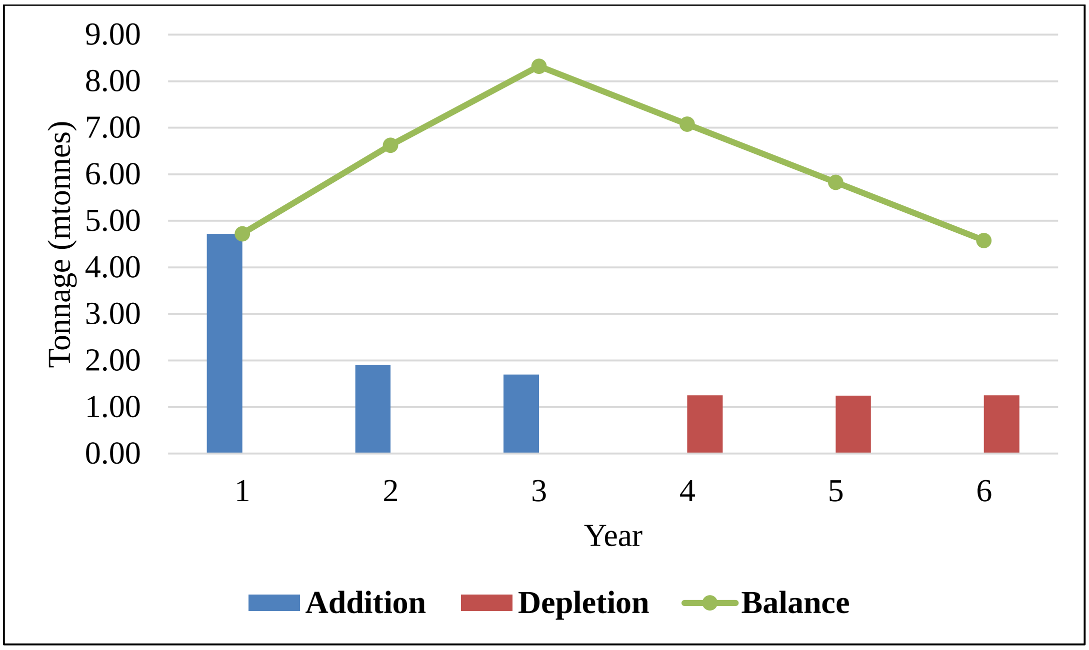


Figure 5.16: SimSched DBS copper equivalent stockpile schedule

Figure 5.17 shows the grade variation over the life of mine. It is worth noting the decline in grade in the second year due to the stripping backlog.

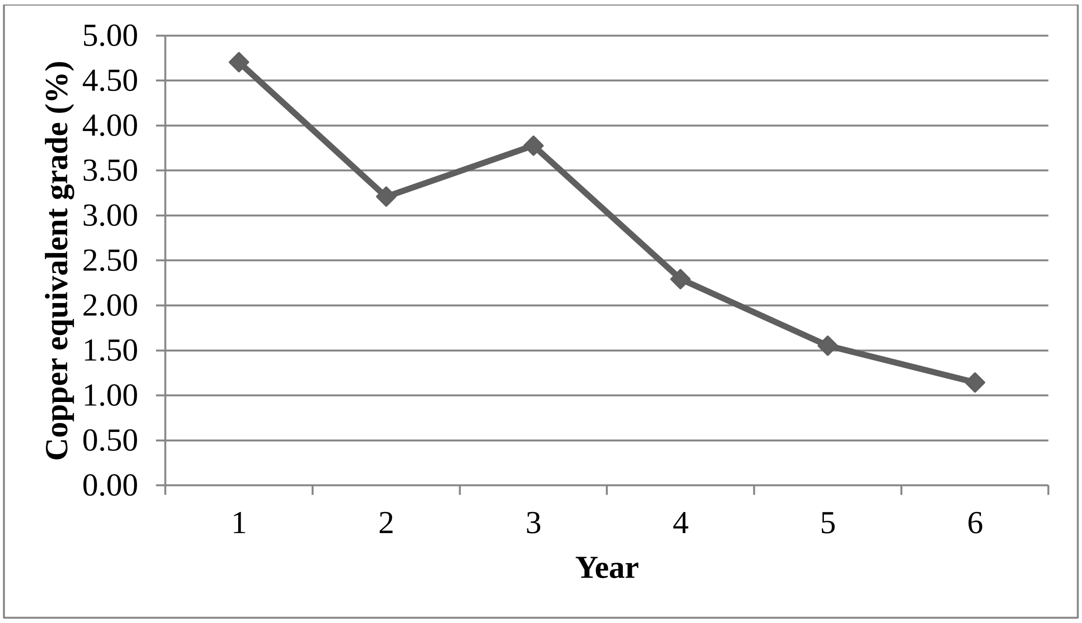


Figure 5.17: Copper equivalent grades variation

The metal output also declines in line with the same pattern as the decline in metal grades. Figure 5.18 shows the copper equivalent metal output over the life of mine.

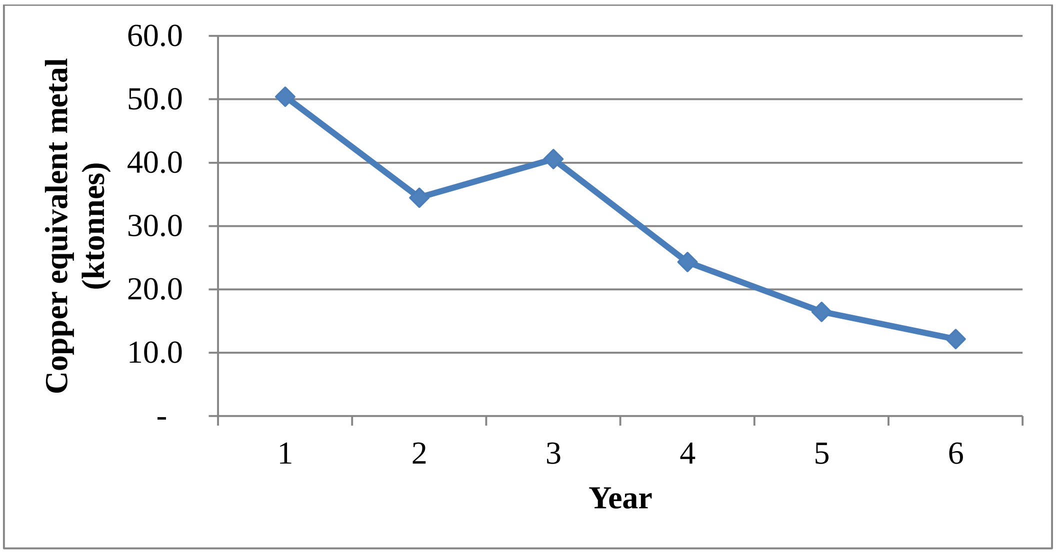


Figure 5.18: Variation of copper equivalent metal output

The NPV also follows the same trend as the metal output. This is based on the assumption that the income from the metal is realised in the year it is produced. Figure 5.19 shows the variation of the NPV over the life of mine.

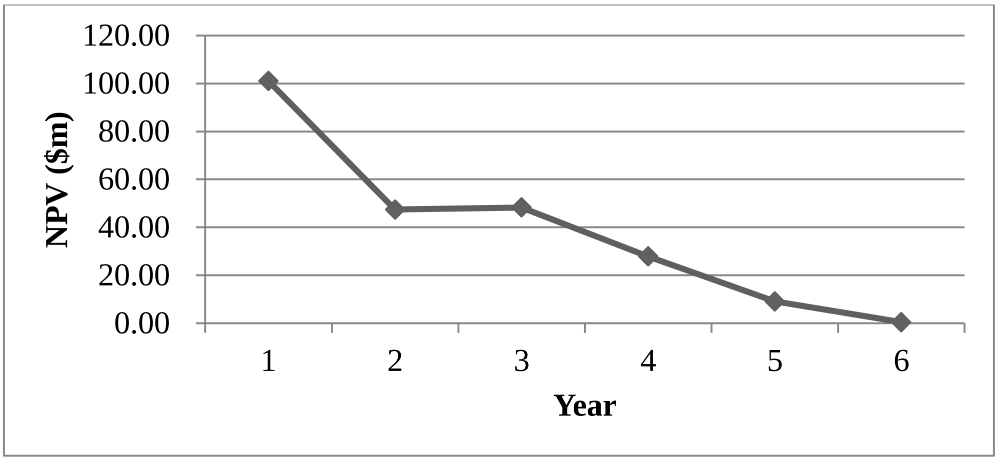


Figure 5.19: Variation of copper equivalent NPV over the life of mine

The cut-off grade optimisation entails processing of those blocks with the highest recoverable values at the beginning of the life of mine. This process is achieved by accelerated mining and the stockpiling of lower value blocks on the stockpile for later processing. Figure 5.20 shows the mining trend over the life of mine. Very high tonnages are mined in the first three years, thereafter the mining declines to only satisfy the mill feed. This was also shown in the massive stockpiling in Section 5.5.2.

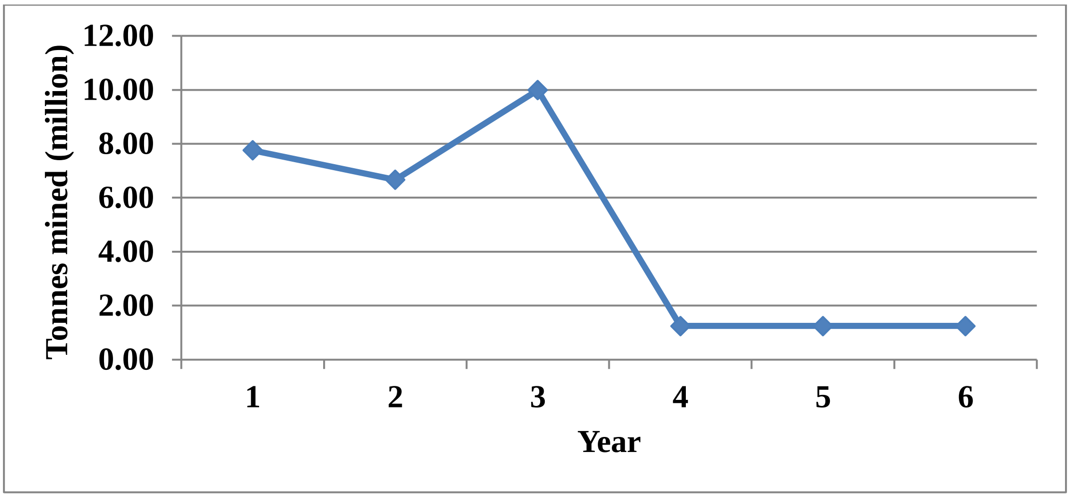


Figure 5.20: Ex-pit mining for copper equivalent life of mine

This cut-off grade optimisation process favours stockpiling and accelerated stripping. For Ruashi Mining, this was exacerbated by years of failing to meet the necessary stripping on a regular basis aimed at reducing costs. The mill throughput is maintained throughout but the metal output decreases to uneconomic levels. This may be improved by reducing fixed costs towards the end of the mine life in order to remain profitable.

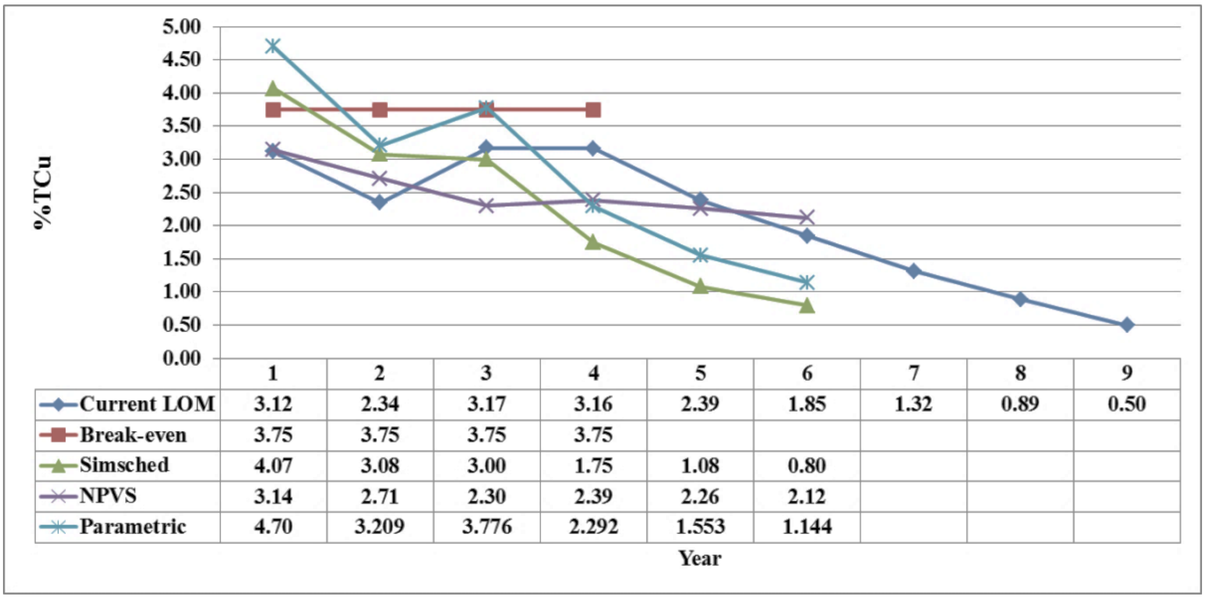
CHAPTER 6: ANALYSIS OF RESULTS

6.1 Introduction

The chapter gives the analysis of results. The scenarios investigated in this report are compared. This comparison includes resultant policies, tonnes mined, life of mine and NPV. Sensitive analysis is conducted in order to evaluate the effects of the various factors like, costs, metal prices and discount rates on the cut-off grade, and hence on NPV. The effects of the environmental costs on cut-off grade are also given. Finally, risk analysis using a trial version of @Risk is conducted.

6.2 Comparison of scenarios

The results have shown that all the methods used and applied to this study adopt a declining cut-off grade policy except for the break-even cut-off policy which remains at the average grade over the mine life. Figure 6.1 compares the cut-off grade policies for the methods investigated. SimSched DBS, NPVS and parametric cut-off grade policies all give a six-year life of mine at declining cut-off grades. The current life of mine cut-off grade policy gives an apparent life of mine of about nine years. This is mainly because the current stockpiles were added and this increases the metal available. The stockpiles were not removed for comparison with the current policy. Massive stockpiling may not be advantageous because of the reclamation costs from the stockpiles.



	1	2	3	4	5	6	7	8	9
Current LOM	3.12	2.34	3.17	3.16	2.39	1.85	1.32	0.89	0.50
Break-even	3.75	3.75	3.75	3.75					
Simsched	4.07	3.08	3.00	1.75	1.08	0.80			
NPVS	3.14	2.71	2.30	2.39	2.26	2.12			
Parametric	4.70	3.209	3.776	2.292	1.553	1.144			

Figure 6.1: Comparison of cut-off grade policies from the scenarios

The stripping backlog is clear in all the scenarios except the NPVS which smoothen the mining. This is shown in Figure 6.2. The current life of mine and the break-even cut-off grade policies both give a four year mining (stripping) life. Thereafter, the pit gets depleted but the processing plant goes on processing ore from the stockpiles for a longer period.

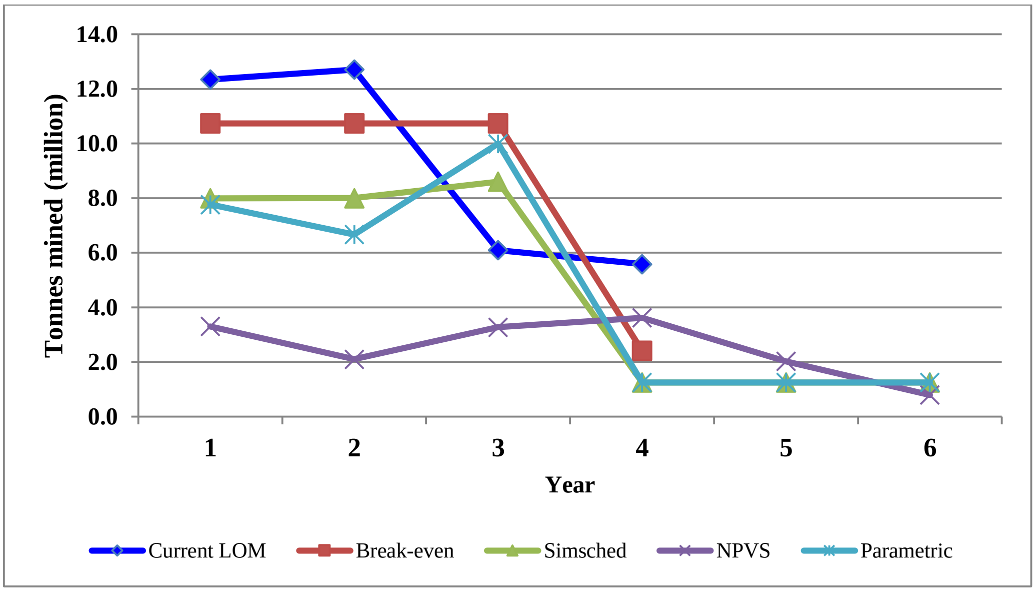
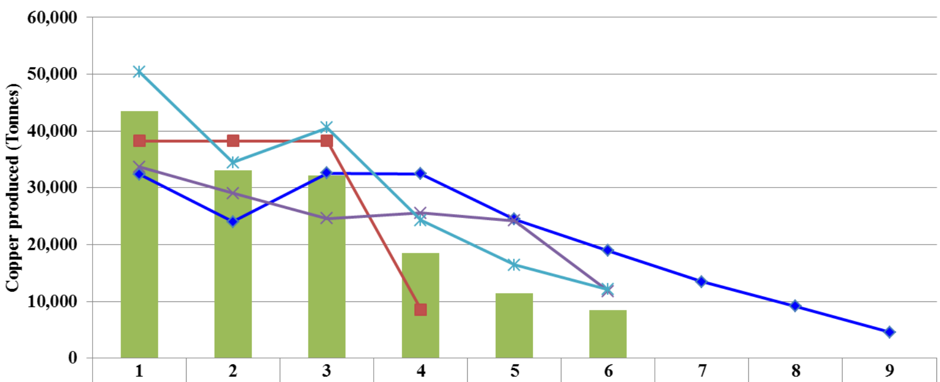


Figure 6.2: Mined tonnages

Copper production is shown in Figure 6.3. Break-even cut-off policy gives a smooth copper output but for the shortest duration. NPVS, parametric and SimSched cut-off grade policies produce copper for six years at declining quantities in line with the cut-off grade policies. The current life of mine graph is included for information only since it is based on more ore compared to the rest of the scenarios due to the inclusion of current stockpiles. The current stockpiles are not included in other scenarios since SimSched DBS does not cater for pre-existing stockpiles.



	1	2	3	4	5	6	7	8	9
Simsched	43,490	33,062	32,209	18,523	11,469	8,455			
Current LOM	32,423	24,067	32,582	32,499	24,514	18,973	13,508	9,158	4,576
Break-even	38,274	38,274	38,274	8,597					
NPVS	33,671	29,061	24,625	25,565	24,215	11,772			
Parametric	50,430	34,490	40,570	24,320	16,470	12,140			

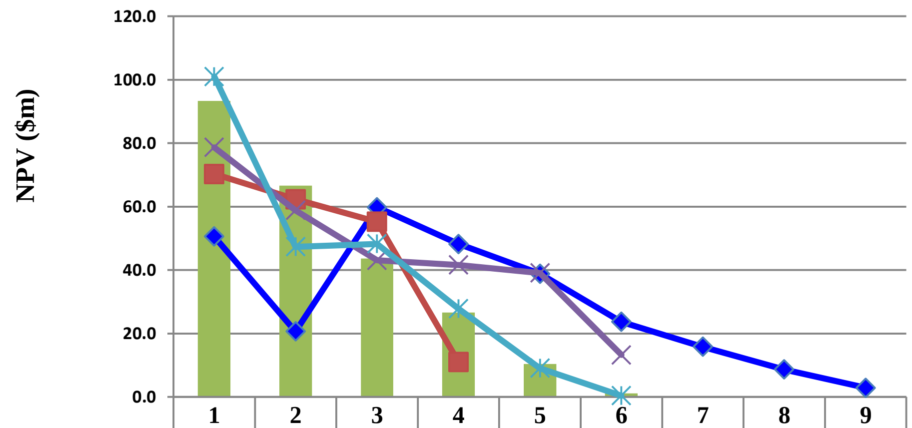
Year

Figure 6.3: Life of mine copper production

The current life of mine is based on schedule optimisation in Geovia MineSched. This optimisation is also based on the current pit design but with no financial input. It is assumed that all the ore inside the design is economic. NPVS has shown that some of the ore in the current pit is not economic to mine. The parametric cut-off produces copper equivalent metal which is a combination of copper and cobalt. That is why the graph starts higher than the rest.

All the scenarios show declining NPV with time as shown in Figure 6.4. As mentioned before, this is caused by the declining cut-off grade policies and hence the declining metal output.

Figure 6.4 shows that the graph for SimSched gives a steady decline in NPV compared to the current life of mine. The current life of mine gives the lowest NPV in the first two years before rising above the rest of the graphs. This caused by the suboptimal stripping to clear the waste mining backlog. There is therefore need to smoothen this by the cut-off grade policy from SimSched DBS.



	1	2	3	4	5	6	7	8	9
Simsched	93.3	66.6	43.7	26.6	10.4	1.1			
Current LOM	50.6	20.7	59.8	48.3	38.8	23.7	15.8	8.7	2.9
Break-even	70.3	62.3	55.2	11.0					
NPVS	78.7	58.9	43.1	41.6	39.1	13.3			
Parametric	101.0	47.4	48.3	27.8	9.1	0.4			

Year

Figure 6.4: Variation of NPV over the life of mine

Comparison of the NPV from the investigated cut-off policies gives the results shown in Figure 6.5. The current life of mine plan was expected to give the highest NPV since it incorporates additional metal from the stockpiles. However, this is not the case due to delayed cash inflows and higher cash outflows caused by increased stripping in the earlier years of the mine life.

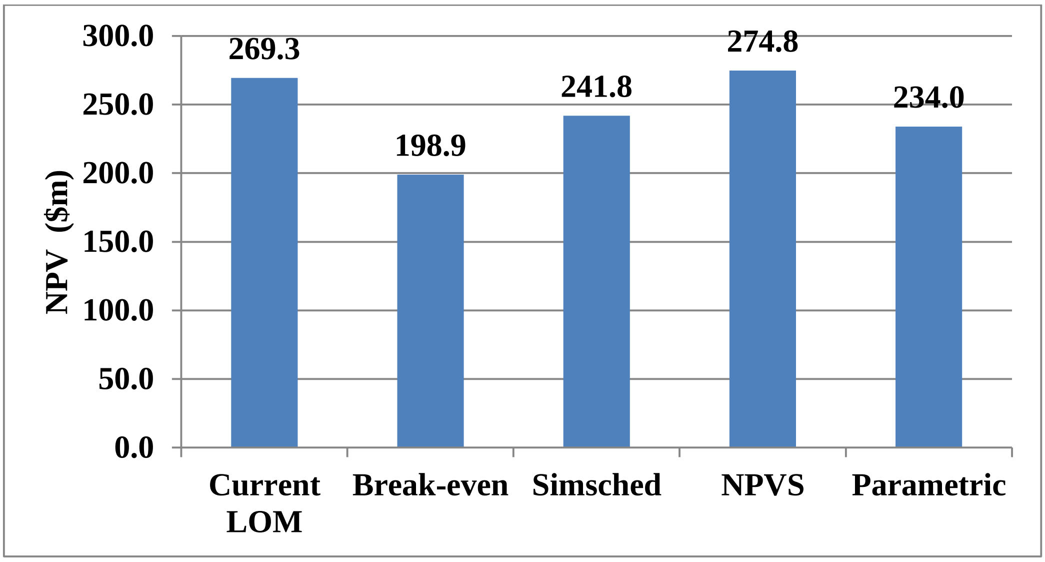


Figure 6.5: Total NPV per scenario

The NPVS gives the highest NPV due to delayed cash outflows by reduced mining at the beginning of the life of mine as shown earlier in Figure 6.2. The NPVS NPV has further been boosted by the removal of the last uneconomic pit which gave a huge negative NPV at the end of the life of mine. SimSched and parametric cut-off are close to each other in terms of NPV because they are based on the same principles. The cut-off grade optimisation based on recoverable value or net smelter return tends to high-grade the mine, especially for a mine with a short life like Ruashi. This then sterilises some of the lower grade ore. The massive stripping and stockpiling at the beginning of the life of mine has a negative impact on the mine life due to higher cash outflows caused by early stripping and re-handle from the stockpiles.

6.3 Sensitivity analysis

6.3.1 Effect of processing costs

Processing costs were varied from 80% to 120% and the effect was then observed. The effect on cut-off grade is shown in Figure 6.6.

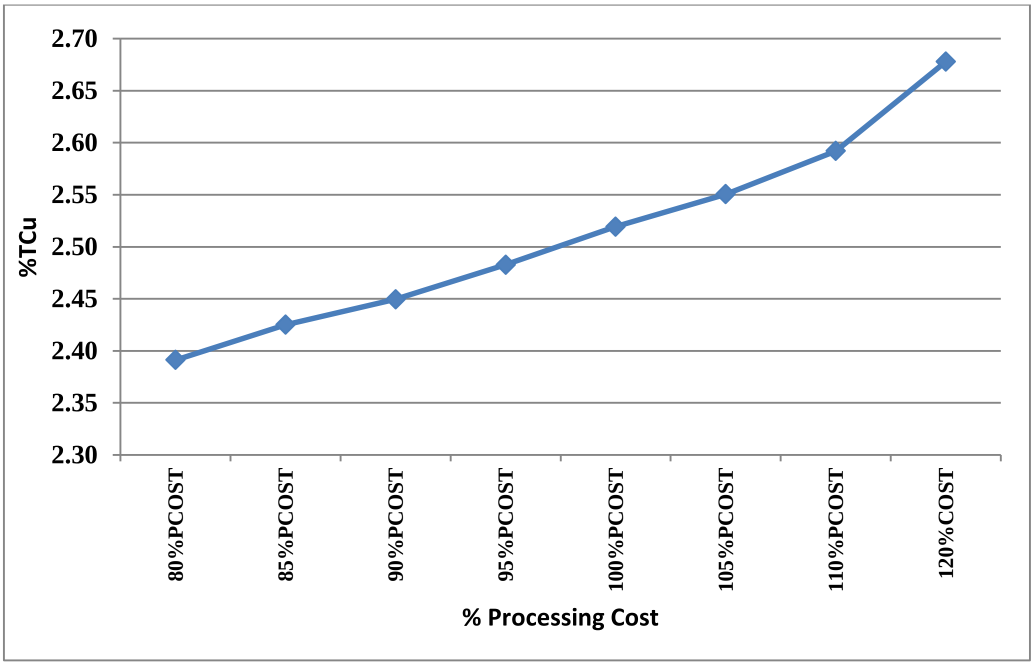


Figure 6.6: Effect of processing costs on cut-off grade

It is observed from Figure 6.6 that the increase in processing costs also increases the cut-off grade. The increase in cut-off grade decreases the ore reserves available for treatment as shown in Figure 6.7.

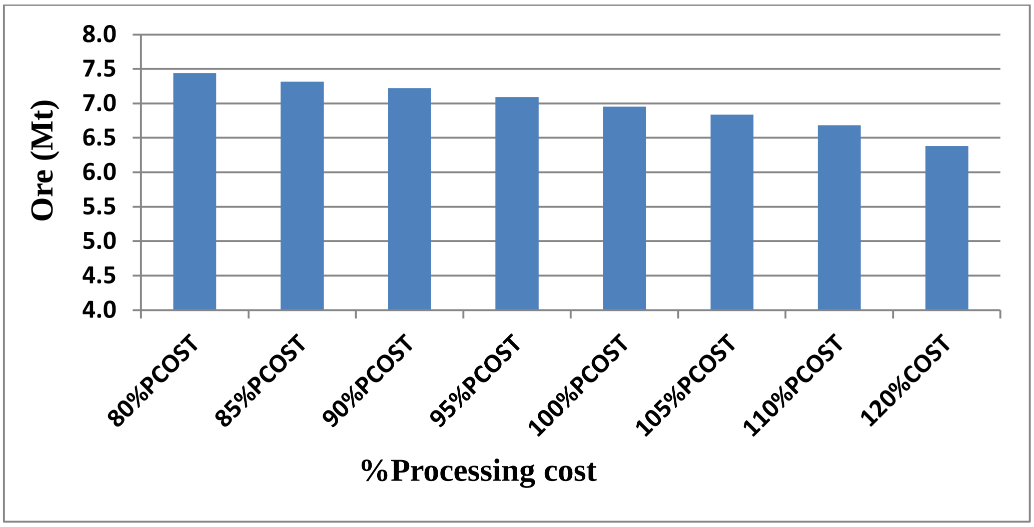


Figure 6.7 Variation of ore reserves with processing costs

The decreased reserves also result in a decrease in metal output as shown in Figure 6.8.

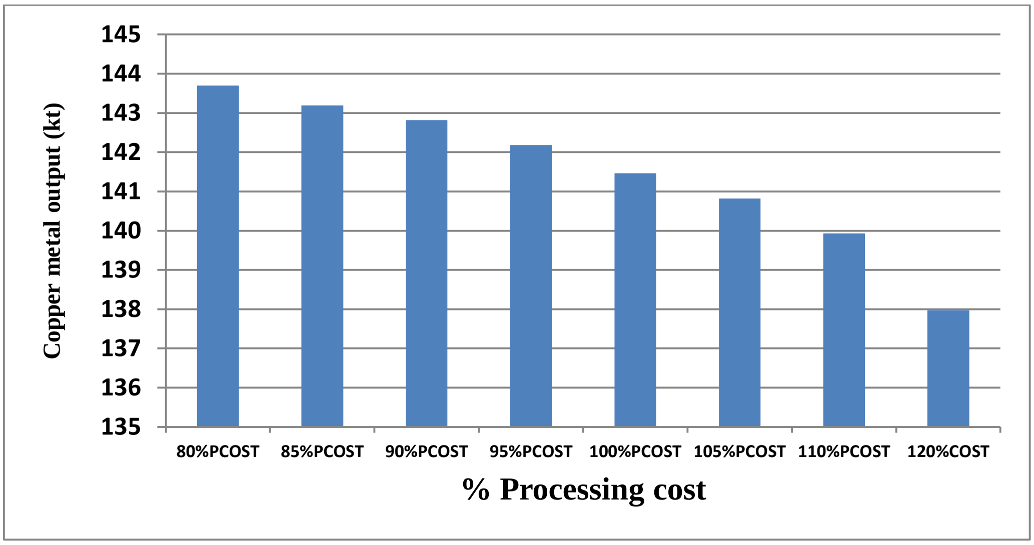


Figure 6.8: Effect of processing costs on metal output

6.3.2 Effect of mining costs

The mining costs were varied from 80% to 120% of the mining costs. The variation of the NPV with mining costs is shown in Figure 6.9. Since there is no significant change in NPV, it follows that the ore reserves are not affected. Small changes to Ruashi mining costs have no major influence on the cut-off grade. This is in line with what was pointed out that mining costs do not influence the processing cut-off grades.

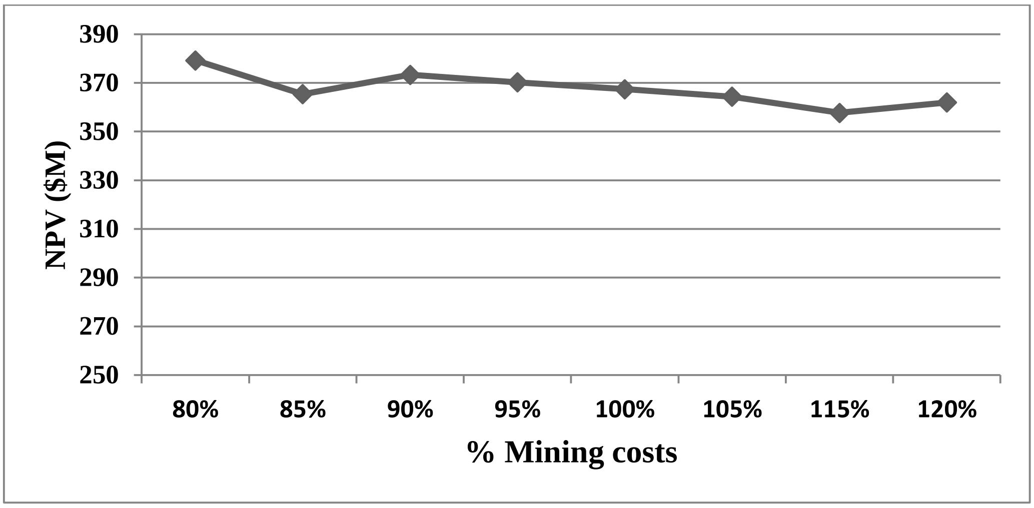


Figure 6.9: Effects of mining costs on NPV

6.3.3 Effect of discount rate

The discount rate was varied from 12.8% to 20%. Table 6.1 shows the variation in grades produced from NPVS.

Table 6.1: Effect of varying discount rate on cut-off grade

Year	12.80%	13%	14%	15%	16%	18%	20%
1	3.14	3.14	3.14	3.14	3.14	3.14	3.14
2	2.71	2.71	2.71	2.71	2.71	2.73	2.73
3	2.30	2.30	2.30	2.30	2.30	2.29	2.29
4	2.39	2.39	2.39	2.39	2.39	2.44	2.44
5	2.26	2.26	2.26	2.26	2.26	2.21	2.21
6	2.12	2.12	2.12	2.12	2.12	2.12	2.12
Average	**2.52**	**2.52**	**2.52**	**2.52**	**2.52**	**2.52**	**2.52**

It is clear from Table 6.1 that varying the discount rate has no effect on the cut-off grades. The discount rate is only used on the profit after all the deductions are made. In this case, the discounting rate is not being treated as a cost and as such it has no part in cut-off grade optimisation. However, the NPV decreases with increase in discount rate. Figure 6.10 shows that all graphs for scenarios with discount rate values above 12.8%

are all below the graph for the base value. This analysis shows that trying to recover capital by increasing discount rate does not work for Ruashi Mining.

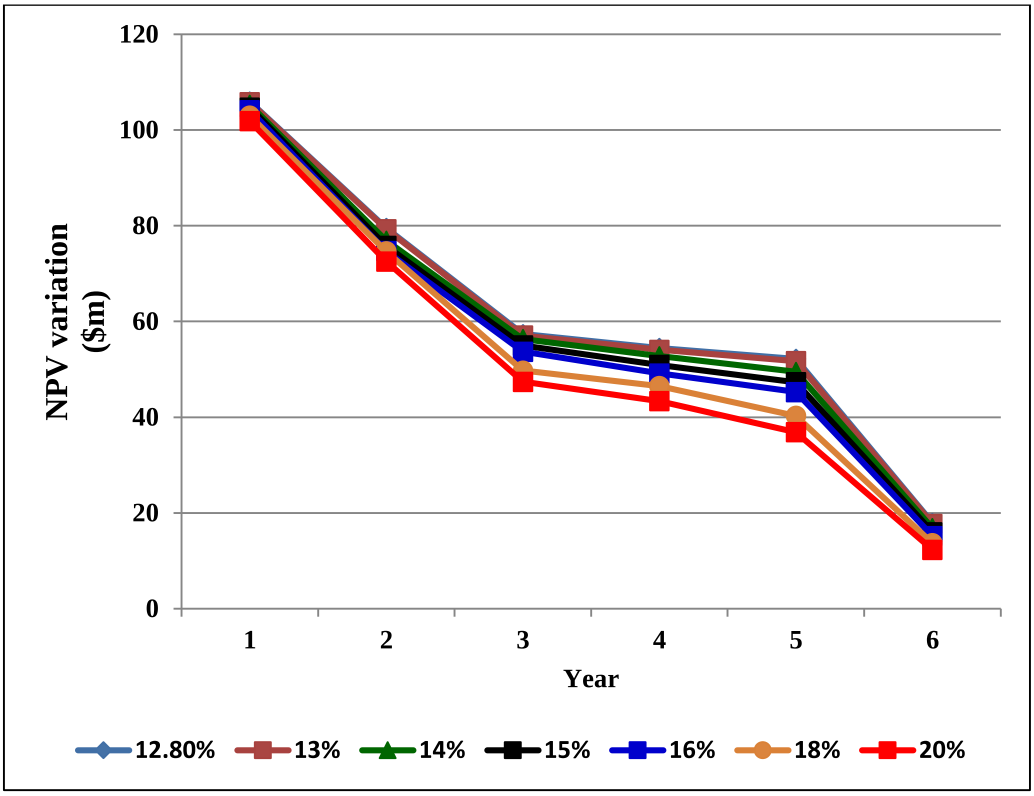


Figure 6.10: Effect of varying discount rate on NPV

The total NPV also decreases when the discount rate is increased. This is given in Figure 6.11. High discount rates have a negative impact on the value for Ruashi.

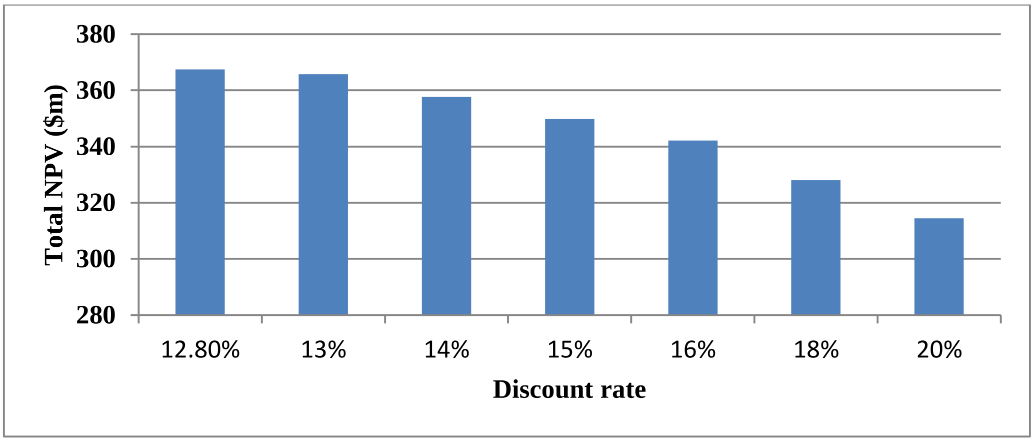


Figure 6.11: Effect of varying discount rate on total NPV

6.3.4 Effect of copper price

The price was varied from 70% to 110% of the long term forecast price. Figure 6.12 shows the variation of the minable average grades as the price was varied. The distribution of the minable grades in the orebody is such that individual trends are not clearly visible. The trend is visible on the minable grades for each percentage change in price.

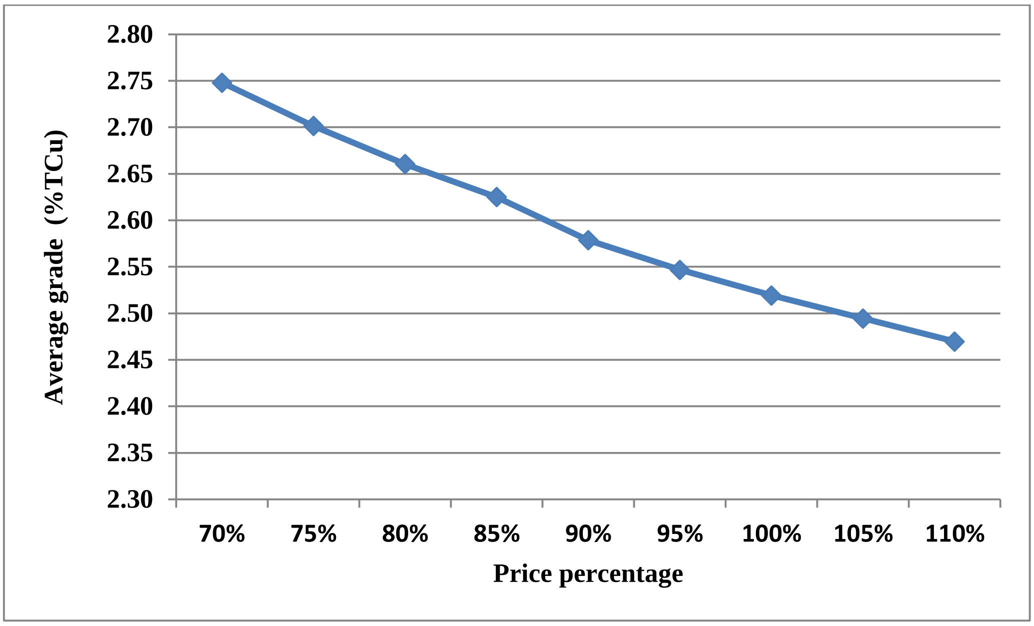


Figure 6.12: Effect of variation in copper price on the cut-off grade

As the copper price is increased the grade decreases. As the price increases, the revenue from a parcel of material exceeds the costs associated with mining, processing and selling the metal produced. Hence, some of the lower grade material that is uneconomic to extract at the lower price becomes economic and lowers the average grade of the ore available for mining which increases the reserves. The effect of price on the reserves is shown in Figure 6.13. An increase in price avails more ore for processing.

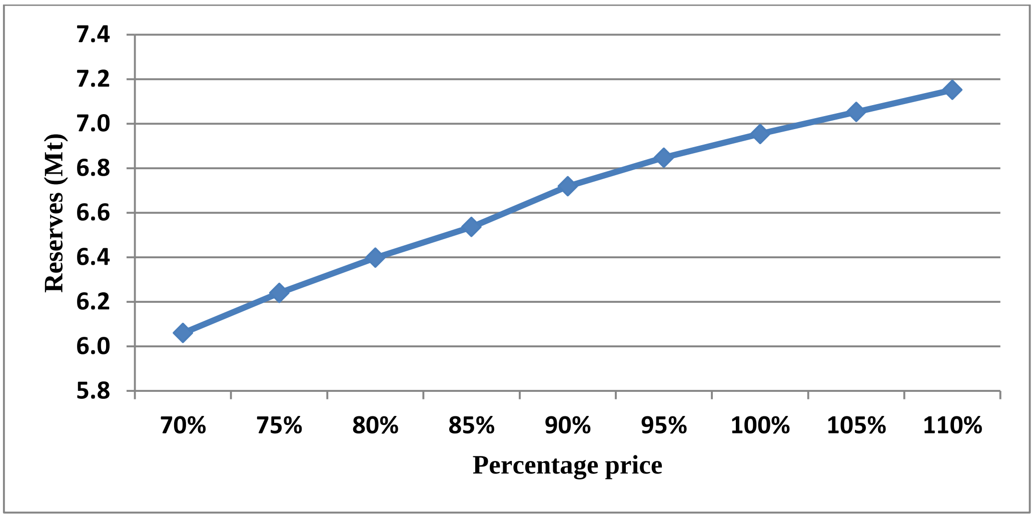


Figure 6.13: Effect of price changes on ore reserves

It also follows that the more the reserves the more the copper produced if the ore characteristics are not affected by the grade. For example, some metal recoveries are a function of the feed grade. However, this is not the case for Ruashi Mining at present. Figure 6.14 shows the variation of copper output with price.

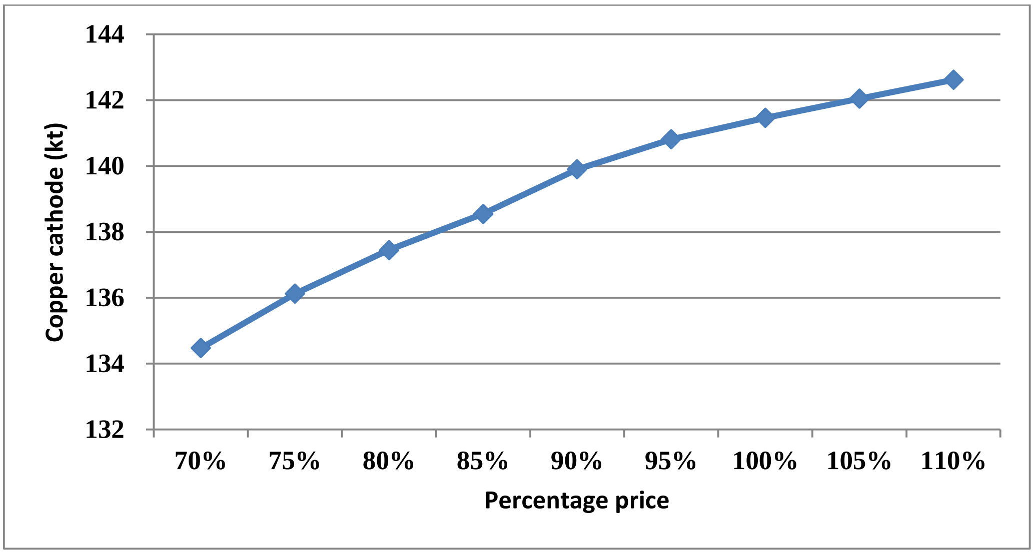


Figure 6.14: Effect of variation in price on copper output

The increased copper output with increase in price implies increased cash inflows and hence increase in NPV. Figure 6.15 gives the variation of NPV with price.

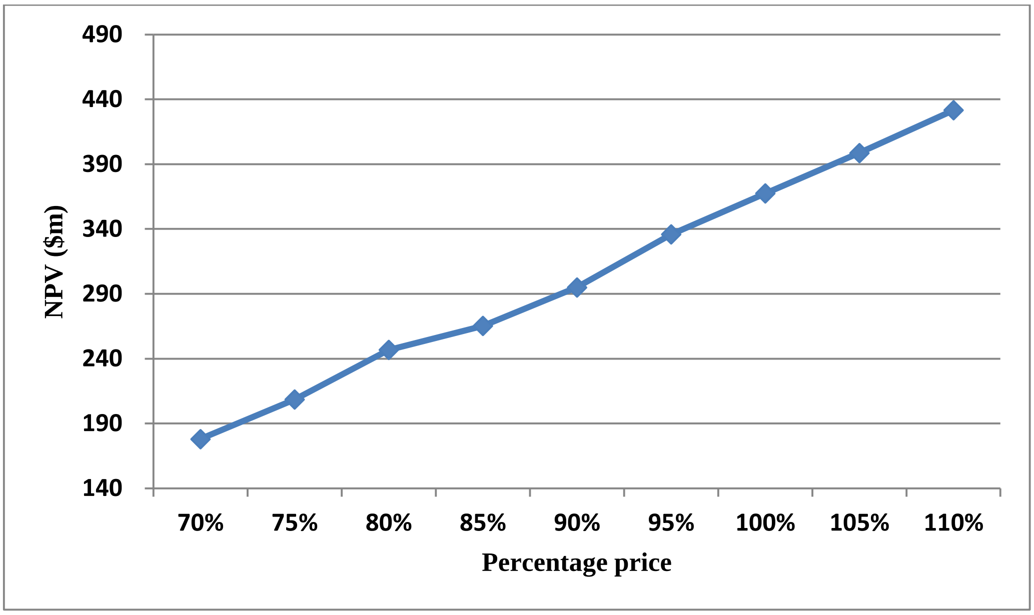


Figure 6.15: Effect of price on NPV

6.4 Cut-off grade incorporating environmental costs

Rehabilitation of waste dumps contributes to the running costs of the mining operation. The waste dump rehabilitation costs were used in the calculation of the processing break-even cut-off grade since Ruashi is mill constrained. Table 6.2 shows the extract from the calculation of the cut-off grade that takes waste dump rehabilitation into consideration. The cut-off grade has decreased from 2.00%TCu to 1.68%TCu. This represents a 16% decrease in cut-off grade.

Table 6.2: Cut-off grade incorporating dump rehabilitation costs

Description	Units	2016
Cu LME Price	$/t metal	6,200
Co LMB Price	$/lb metal	2.96
Cobalt sales - % of LMB price	%	69.50%
Mining cost - average	$/t mined	5.59
Processing cost	$/t milled	43.87
Element processing - Cu	$/t Cu contained in feed	671.35
Element processing - Co	$/t Co contained in feed	3,802.89
Time Costs	$	87,740,769
Unit Time Costs	$/t milled	77.90
Selling cost per tonne - Cu	$/t metal	495.88
Selling cost per tonne - Co	$/t metal	2,574.20
Copper royalty	%	0.961
Cobalt royalty	%	0.961
Discount rate	%	0.13
Unit environmental cost	$/t	0.389
Plant capacity	t/year	1,387,000
Copper recovery		0.85
Cut-off grade	**%**	**1.68**

The calculation shows that environmental costs considerations favour lower cut-of grade in order to minimise the amount of waste generated. The low amount of waste generated means reduced environmental pollution. Hence, it is crucial to consider environmental costs in the calculation of cut-off grades for Ruashi. This was not implemented in this research since dump rehabilitation is at an advanced stage at Ruashi Mining, therefore a more detailed needs to be done in order to have a more representative cost regime.

6.5 Risk analysis using @Risk

Guj (2013) defines risk as the potential for negative outcomes compared to one's objectives. This separates risk from opportunity which is the potential to realise higher gains than expected. It is the objective of risk analysis to identify and quantify the effects of risk or opportunity.

There are many ways of conducting risk analysis. The software called @Risk which was developed by Palisade Corporation is used for conducting risk analysis and modelling in Microsoft Excel. @Risk uses Monte Carlo simulation to model risk and gives results in Microsoft Excel (Palisade Corporation, 2004). Probability distributions are used as data inputs in simulation instead of using single values (Hall, 2014).

As noted by Guj (2013), many natural phenomena normally follow the lognomal distribution. Table 6.3 shows the assigned distributions for the various inputs in SimSched DBS optimisation output.

Table 6.3: Assigning probability distributions to SimSched DBS optimisation output

Description	Distribution
Cu LME Price	Lognormal
Co LMB Price	Lognormal
Mining cost - average	Lognormal
Processing cost	Lognormal
Element processing - Cu	Lognormal
Element processing - Co	Lognormal
Unit Time Costs	normal
Selling cost per tonne - Cu	normal
Selling cost per tonne - Co	normal

The distributions were assigned as shown in Table 6.3 in the @Risk software to investigate the impact of each of the input parameters on the NPV. The Tornado diagram in Figure 6.16 shows the effect of the various parameters on the NPV.

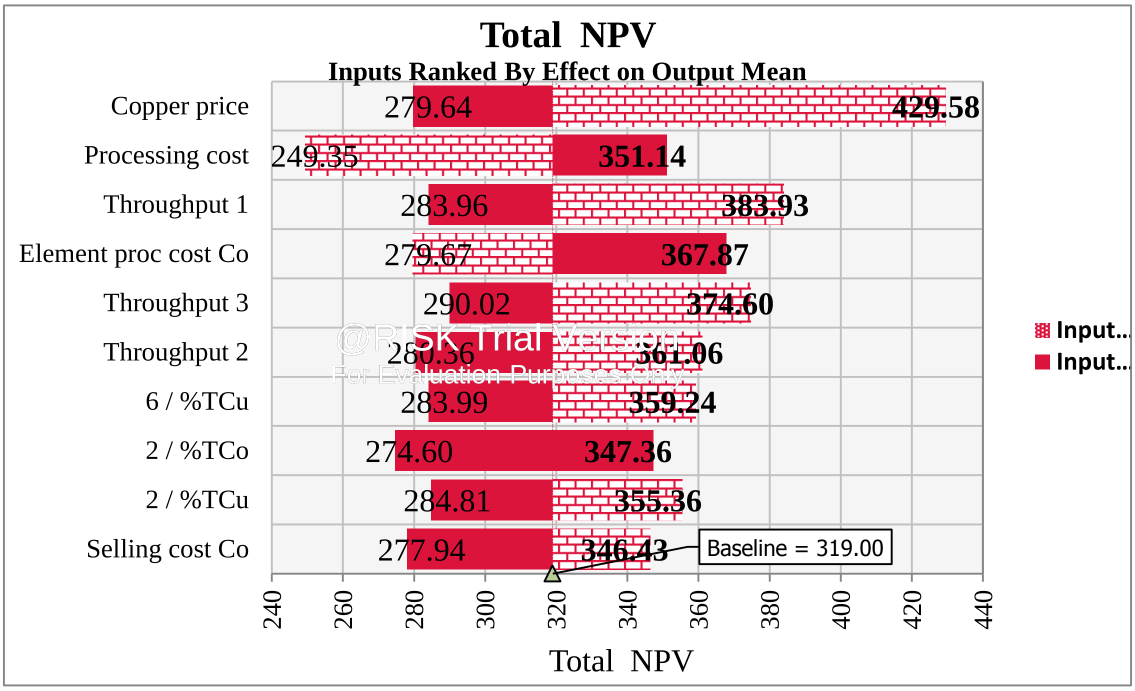


Figure 6.16: Tornado diagram - ranked effects of inputs

The copper price has the highest impact on the cut-off grade. Notably, high prices are also essential for higher NPV, low prices reduce it. Price forecasts need to be as accurate as possible in order to maximise the NPV. High throughput and high grades also contribute to high NPV. High processing costs have a huge negative impact on the NPV. Figure 6.16 makes it clear which parameters are worth the focus for Ruashi.

The initial calculated NPV is $241.80. Risk analysis using @Risk shows that there is a 91% probability of getting a higher NPV than the original estimate. This is shown in Figure 6.17.

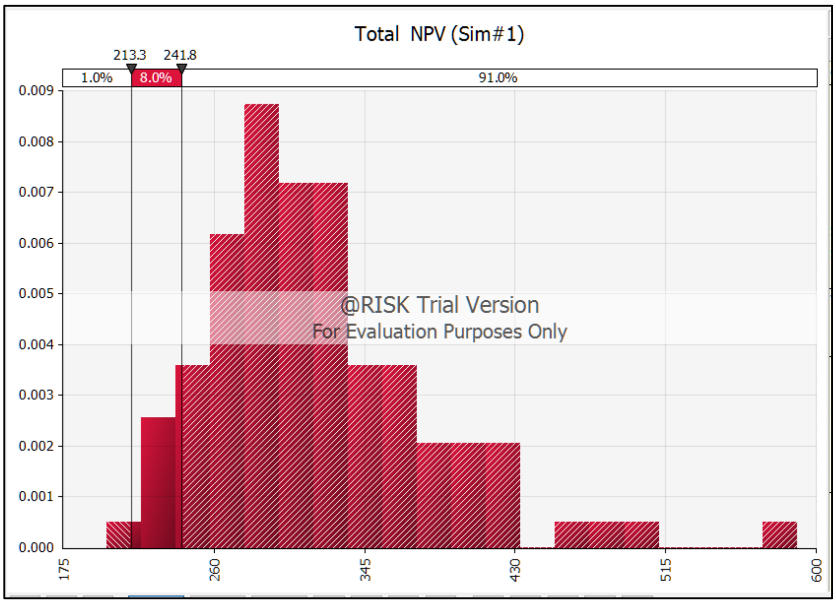


Figure 6.17: Probability of improving NPV above base value

As such if this risk analysis was conducted in order to evaluate the risk or opportunity of achieving the estimated NPV then the results show that the project can go ahead because of the high likelihood of success. On the other hand, the probability of the project failing is zero as shown in Figure 6.18.

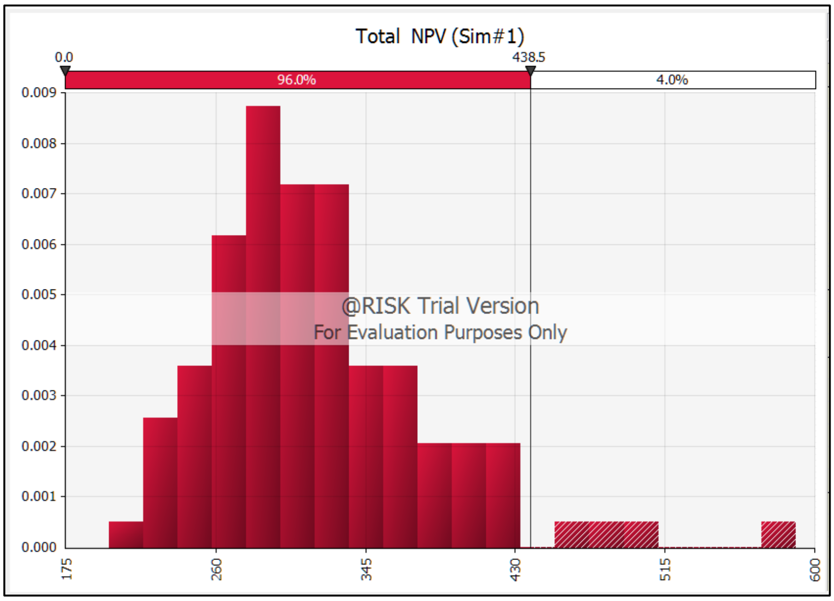


Figure 6.18 Probability of making a loss for Ruashi

@Risk has actually shown that the NPV needs to be improved by about 143% by varying the relevant inputs.

6.6 Chapter summary

Of the investigated scenarios, it has been shown that the break-even cut-off grade policy gives the shortest life of mine. SimSched DBS promotes production of more metal in the early years of the life of mine. The effects of the waste stripping backlog have been mitigated by following a cut-off optimisation policy.

The results have shown that mining costs have no effect on the processing cut-off grade. However, the increase in metal price lowers the cut-off grade and vice versa. Taking environmental costs into consideration lowers the cut-off grade. @Risk was also used to identify risks and opportunities in cut-off grade optimisation for Ruashi.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The research was aimed at addressing the following:

- The stripping backlog incurred in the past which is destroying the value of Ruashi Mining;
- Unavailability of high grade ore due to previous high-grading which threatens the premature closure of the mine;
- The opportunity to improve the Net Present Value (NPV) of Ruashi Mining in cognisance of the prevailing operational challenges.

The life of mine schedule produced from SimSched DBS has given an optimised cut-off grade policy which can be applied at Ruashi. The mill feed grades are also targeted based on the ore that can be availed in a particular year. The scheduled mining periods are displayed in different colours in Figure 3.5. The periodic surfaces can be exported to other mine design software and used to control the mining process so that the targeted grades are achieved. The surfaces are used as constraints to prevent mining of unplanned ore and to ensure the planned waste is mined accordingly.

Proper scheduling of waste stripping through cut-off grade optimisation has shown that the high grade ore can be availed starting in the first year of the life of mine. All the three methods used to produce the cut-off grade policy have shown that high grade ore can be can be availed in the early years of the life of mine.

There is an opportunity to improve the NPV of Ruashi mining by optimising the cut-off grade. The comparison of the NPV from the current life of mine against that produced by the three scenarios in Figure 6.5 attests to that. The current life of mine includes ore from the current stockpiles which is not included in the scenarios. If the stockpile ore is included, the NPV might be way above that of the current life of mine.

Care needs to be taken however, due to the high influence of cobalt price on the block values that may cause high-grading. This has been shown by the sterilisation of lower grade material which is not economic to treat anymore because it fully utilises the full plant capacity without much metal output. NPVS seems not be as aggressive as SimSched in maximising metal output, hence it gives a smoother schedule.

The metal equivalent grade gives almost the same results as the Net Smelter Return (NSR) in SimSched even though it is slightly lower. In this case copper equivalent was used. It simplifies the optimisation process but may not be ideal for further economic analysis. It is important to know how much of each metal is being produced although the back calculation becomes cumbersome.

The break-even cut-off grade gave the lowest NPV of all the scenarios investigated. This shows that running a mine on break-even cut-off grade does not optimise the value of the operation. As such, this cut-off grade must only be used as a quick estimation.

Risk analysis conducted using @Risk software has shown that it is possible to improve the NPV from that based on SimSched DBS by focusing on the critical input parameters like lowering processing costs, increasing throughput and optimising the cut-off grade policy. @Risk has also shown that unless something catastrophic happens, Ruashi's NPV will always be positive based on the investigated parameters.

7.2 Recommendations

It is necessary to control the mining rate in the earlier years of the life of mine in SimSched DBS to prevent high cash outflows at the beginning of the life of mine. The scheduled mining rate is astronomically high in the first three years. This results in huge stockpile volumes. This ties up a lot of capital in the stockpiled ore, which is not in line with the time value of money. To optimise NPV, it is necessary to maximise cash inflows and delay cash outflows as much as possible without damaging the reputation of the company. Delaying cash outflows can be achieved by reducing the mining rate at the beginning of the life of mine. The NPV from SimSched could have been much higher with a reduced mining rate. It is a bit of a challenge for Ruashi to reduce the mining rate due to the short mine life.

There are a lot of calculations outside the SimSched DBS programme. It is necessary to have SimSched generate block economic values automatically so as to make the program more user-friendly. This also makes the optimisation runs even faster from a human point of view. It is also necessary to have SimSched convert the coordinates of the block model to indices without the user having to do it manually. The aim is to try to reduce human errors as much as possible.

The optimisation on block economic value has tended to have high-grading effect on the Ruashi orebody which is a bimetallic orebody. The by-product has a higher unit price compared to the core product. This has resulted in the inclusion of blocks with copper grades below the break-even cut-off grade. This results in scheduling of very low grades which might not be practical for metal recovery in the plant. Incorporating a way to prevent mining of uneconomically low grades may assist in preventing this.

There is also need to cater for pre-existing stockpiles in SimSched for a complete cut-off grade optimisation. At the moment SimSched just caters for material from the model only. In many cases stockpiles are not modelled but the tonnages and average grades are known.

Parametric cut-off grade is ideal for simplifying cut-off grade optimisation for polymetallic deposits. However, it becomes necessary to revert to component grades for further economic analysis beyond the cut-off grade optimisation. The parametric cut-off grade conceals the parameters which the engineer can use to benchmark with other operations. It is also necessary to know the quantities of specific products. As a result, it is the researcher's feeling that parametric cut-off grades are only more useful academically.

Fixed recoveries have been applied for all grades of the ore. This might be overvaluing the deposit because recoveries commonly decrease with ore grade. A study needs to be conducted to investigate this assumption for Ruashi Mining. This will enable the determination of the relationship between feed grade and metal recovery.

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APPENDIX A

Cut-off grade calculation formulae

(William, 2014)

$$Planning\ cut-off\ grade = \frac{\mathrm{m} + \mathrm{h} + (\frac{\mathrm{f} + \mathrm{F} + \mathrm{X}}{\mathrm{H}})}{(\mathrm{p} - \mathrm{k})\mathrm{y}}$$

$$Budget\ cut-off\ grade = \frac{\mathrm{m} + \mathrm{h} + (\frac{\mathrm{f} + \mathrm{C} + \mathrm{C}}{\mathrm{H}})}{(\mathrm{p} - \mathrm{k})\mathrm{y}}$$

$$Accounting\ cut-off\ grade = \frac{\mathrm{m} + \mathrm{h} + (\frac{\mathrm{f} + \mathrm{F} + \mathrm{C} + \mathrm{X}}{\mathrm{H}})}{(\mathrm{p} - \mathrm{k})\mathrm{y}}$$

$$Break-even\ cut-off\ grade = \frac{\mathrm{m} + \mathrm{h} + (\frac{\mathrm{f} + \mathrm{X}}{\mathrm{H}})}{(\mathrm{p} - \mathrm{k})\mathrm{y}}$$

$$\mathrm{Marginal\ cut-off\ grade} = \frac{\mathrm{s} + \mathrm{h}}{(\mathrm{p} - \mathrm{k})\mathrm{y}}$$

Where

m = mining variable cost

f = fixed cost

F = opportunity cost

X = ongoing capital expenditure

H = treatment capacity

C = minimum profit or net cash flow

p = price

k = variable marketing cost

y = yield (recovery)

s = rehandle cost from stockpile