School of Mining Engineering

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

UNDERSTANDING THE IMPACT OF THE SOUTH AFRICAN MINERAL RESOURCE ROYALTY REGIME ON TABULAR GOLD DEPOSITS: AN APPROACH FOR CUT-OFF GRADE OPTIMISATION.

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A thesis submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering.

Johannesburg, 2022

DECLARATION

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“The ore body dictates.”

Bernard Swanepoel

ABSTRACT

The South African mineral resource royalty introduced in 2010 employs a hybrid *ad valorem* approach in which the rate depends on the profitability ratio. This rate is then applied to the base of the total revenue from mineral sales. The fundamental purpose of this research is to understand how the profitability ratio in the mineral resource royalty interplays with the gold tax formula applied to South African gold mines and to develop an approach for cut-off grade optimisation. Narrow, tabular (Witwatersrand) gold mines are used for this study. The method developed is a mixed-integer (Excel Solver) cut-off grade optimiser that uses the mine's block list and ore flow documents and feeds this into a financial cash flow which includes the appropriate royalty and income tax formula. This could then be utilised to test various mineral resource royalty cost options.

This research shows that the impact of the royalty is minimal because the analysis convincingly proves that it is more neutral than expected. Simply ignoring the mineral resource royalty costs when determining the cut-off grade by a break-even approach increases the profit slightly compared to including the expected costs. However, resource utilisation increases significantly, allowing the benefits of reduced development costs. Furthermore, life is added to the mines, which is very beneficial in a country with high unemployment. Total revenue and tax contributions also increase significantly.

Further gains can be achieved using the optimiser model developed for this study that recognises the profitability aspect of the mineral resource royalty and the income tax (gold tax) formulae. This optimiser also allows a multiple-criteria cut-off grade optimising approach and grade estimation uncertainties to be considered. This is an appropriate method to optimise the capability of the ore body and should be considered by the industry when deciding and reporting mineral reserve statements for narrow-reef gold mining.

PUBLICATIONS AS PART OF THIS RESEARCH

The publications listed below have emanated from this research work so far:

Birch, C. (2016). Impact of the South African mineral resource royalty on cut-off grades for narrow, tabular Witwatersrand gold deposits. Journal of the Southern African Institute of Mining and Metallurgy. 116(3).

Birch, C. (2016). Impact of discount rates on cut-off grades for narrow tabular gold deposits. Journal of the Southern African Institute of Mining and Metallurgy. 116(2).

Birch, C. (2017). Optimization of cut-off grades considering grade uncertainty in narrow, tabular gold deposits. Journal of the Southern African Institute of Mining and Metallurgy. 117(2).

Birch, C. (2018). Review of cut-off grade optimisation from Southern African mines. Student assignment based observations. Resources Policy. 56(C).

Birch, C. (2019). Optimisation of Mining Block Size for Narrow Tabular Gold Deposits. In Proceedings of the 27th International Symposium on Mine Planning and Equipment Selection - MPES 2018 (Santiago, Chile).

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation	Description
AIC	all-in costs
AISC	all-in sustainable costs
AMG	average mining grade
ANC	African National Congress
CapEx	capital expenditure
CAPM	capital asset pricing model
CF	cash flow
CRG	Central Rand Group
CW	channel width
DCF	discounted cash flow
EBIT	earnings before interest and tax
GGM	Gordon growth model
GRG	generalised reduced gradient
GSR	gross sales revenue
IRR	internal rate of return
JCI	Johannesburg Consolidated Investments
LoM	life-of-mine
LP	linear problems
MCF	mine call factor
MPES	mine planning and equipment selection
MPRDA	Mineral and Petroleum Resources Development Act 28 of 2002
MPRRA	Mineral and Petroleum Resources Royalty Act 29 of 2008
MRF	mine recovery factor
MRRT	mineral resource rent tax
MW	milled width
NCF	net cash flow
NPV	net present value
$NPV_{9\%}$	the net present value at 9 % discount rate
$NPV_{12\%}$	the net present value at 12% discount rate
OpEx	operating expenditure

PCF	plant call factor
PhD	Doctor of Philosophy
RD	relative density
SIMS	State Intervention in the Mining Sector
SMU	smallest mining unit
SW	stoping width
TCC	total cash cost
TFC	total fixed costs
TR	total revenue
TUC	total unit cost
TVC	total variable costs
TVM	time value of money
UR	unit revenue
UVC	unit variable costs
VAT	value-added tax
VCR	Ventersdorp Contact Reef
WACC	weighted average cost of capital
WGC	World Gold Council
ZAR	South African Rand

Symbol	**Description**	**Units**
a	area	m^2
$Au(g)$	gold content	g
$Au(oz)$	gold content	oz
cmg/t	centimetre grams per tonne	cmg/t
CW	channel width	cm
g/t	grams per tonne	g
i	interest/discount rate	%
ist	in situ tonnage	t
it	income tax	US$
mc	mining cost	US$/t

MCF	mine call factor	%
MRF	mine recovery factor	%
MRR	mineral resource royalty	US$
Mt	million tonnes	t
MW	milled width	cm
oz	troy ounce	oz
p	profit	US$
pl	pay limit	g/t
PCF	plant call factor	%
pr	price	US$
r	recovery	%
rev	revenue	US$
S/M	ratio of stope to milled tonnage	%
SW	stope width	cm
t	tonnage	t
t/a	tonnes per annum	t
TR	total revenue	US$
x	profit/revenue ratio	%
X	volume	t
$Y(\%)$	income tax rate	%
$Y(ur)$	unrefined royalty rate	%
$Y(r)$	refined royalty rate	%

1 INTRODUCTION

Establishing an appropriate taxation system is difficult due to conflicting needs and objectives. Each country's circumstances are different, which must be considered when defining appropriate mineral taxation and royalty regimes (Otto & Cordes, 2002). South Africa's economy is considered a developing economy (Johnson & Pintz, 1985; Bakari, 2017). The following features are common to almost all developing economy countries' mineral policies:

- The extractive industries should generate revenue for the national treasury;
- The State should exercise some direct ownership and control over the extractive industries; and
- The extractive industries should serve more considerable development and regional growth goals or provide employment opportunities (Johnson & Pintz, 1985).

The exhaustible aspect of mineral resources imposes a finite period for which countries can obtain financial benefits from the resource. Governments use a range of fiscal instruments to obtain this benefit, including royalties, company income tax, employee income tax (also termed holding tax or people tax), dividends tax, value-added tax (VAT), social and labour plan contributions, skills development levies, and excise duties and levies, including the fuel levy (Johnson & Pintz, 1985; The South African Revenue Service, 2021).

The taxation of mining companies has become a topical subject in the post-apartheid South African economy. There have been increasing calls for equitable re-distribution of mineral asset wealth to benefit all South African citizens. As part of the Mineral and Petroleum Resources Development Act (MRDPA) of 2002, the Mineral and Petroleum Resources Royalty Act (MPRRA) of 2008 was introduced and implemented in 2010 (Payne, 2008;

The South African Government, 2008). A mineral royalty is a payment to the mineral rights holder for utilising the mineral resource. If the mineral rights holder is the State, this payment is made to the State (Cawood, 1999). Studies on the impact of the mineral resource royalty on the minerals industry were conducted to determine its construction. These include Cawood and Macfarlane 2003, who suggested a cap of 3% and Cawood in 2011, which predicted rising cut-off grades and thus reduced mineral reserves. A study by Zwan and Nel (2010) concluded that the introduction of the MPRRA could significantly adversely affect the South African mining industry. Their study suggested that reduced profits would affect the extractors' economic decisions, resulting in them investing elsewhere (Van Der Zwan & Nel, 2010). In 2014, Grobler concluded that the impact of the mineral resource royalty on the economy was buoyant. She stated that the effect has caused operating expenses to increase, but this does not appear significant. Furthermore, she noted that the impact had not affected how the mining industry works (Grobler, 2014).

Otto and Cordes (2002) identify the impact of royalties on determining the cut-off grades. *“Grades that fail to generate revenues greater than costs will be left in the ground”* (Otto & Cordes, 2002: 7–24). Royalties not based on net revenues can potentially increase the cut-off grades due to reducing the overall levels of recovery (Otto & Cordes, 2002). *“Poorly designed and executed policies may entail more costs than benefits for society.”* (Tilton & Guzmán, 2016: 116). For private companies, the objective function is assumed to be profit, except where higher short-term profits lead to lower profits in future years. In this case, it may be assumed that maximising the net present value (NPV) of current and future profits would be the primary goal (Tilton & Guzmán, 2016). There are exceptions where mines decrease their cut-off grades when metal prices are high to extend the resource utilisation to benefit the local community and ensure employment for as long as possible (Tilton & Guzmán, 2016). In this case, the interests of the mine start to overlap with the interests of governments. Governments should serve their citizens' interests and set policies that maximise society's welfare (Tilton & Guzmán, 2016).

Lilford (2017) identified that very little research had been conducted on the impacts of mining taxes and royalties on the mining deposit relating to the cut-off grade and the resultant mineral sterilisation and life of the mine. He pointed out that ideally, the company and the State would be equitably satisfied, but this is seldom the case (Lilford, 2017). If the mineral resource royalty was just levied on profit, it could be ignored for cut-off grade purposes, as is the case for income tax. However, because it is imposed on total sales, *ad valorem* and mining volume royalties should be considered a cost in determining the cut-off grade (Hall, 2014). Mines determine the cut-off grade and use this to indicate what is considered ore and waste. An increase in cut-off grade due to the rise in costs (including the mineral resource royalty) reduces available mineral reserves above the calculated cut-off grade. This study aims to consider how the cost of the mineral resource royalty has increased cut-off grades to a selection of gold mines and determine the impact on overall revenue generated for the State. This study then determines how these mines could optimise their cut-off grades considering the mineral resources royalty, especially where there is an interplay with other forms of taxation. This study differs from previous studies found during the literature review in that a selection of individual mines is considered, and the impact on their ore bodies is determined. Each ore body has a unique grade distribution. Thus, it is expected that this will result in differences in how the economics of the ore body is impacted by the additional costs associated with the mineral resource royalty.

The impact of income tax (gold tax formula) and royalty payments on the life of the mine and how much of the resource gets converted into reserves as a function of the economic benefit will be considered in this study. There is an increasing demand for mining companies to address the social and cultural needs of the communities within which they operate. It benefits all stakeholders if mines utilise the full potential of the ore body. In the State

Intervention into the Mining Sector (SIMS) document, it is argued that the State should be allowed a more significant portion of the profits (‘supertax or windfall tax”) (African National Congress (ANC), 2012). It was implied that the resource royalties’ tax in its current form is not achieving this. The SIMS document (released in June 2012) called for reviews of how the State receives revenue from the mining sector. A suggestion is made that the Australian mineral resource rent tax model could be considered (Parliamentary Monitoring Group, 2013). There could thus be changed in the future in how the mineral resource royalty is structured. However, this study focuses on the mineral royalty in its current form and how it affects mine planning and investment decisions.

Two primary forms of taxation will primarily be considered for this study: the income tax (in the form of gold tax for gold mines) (South African Revenue Service (SARS), 2022) and the mineral resource royalty (The South African Government, 2008). The gold taxes and the mineral resource royalty both have sliding scales based on the operation's profitability. In periods with higher profitability, the structure of these taxes results in a higher tax percentage of the revenue generated to be paid to the State. The difference between the two forms of taxation is the base they are levied on. Income tax is paid as a percentage of the profit, while mineral resource royalty is paid on a base allowing for a few deductions – almost total gold sale revenue. These two taxes address the State's issue of not receiving a higher portion of the revenue at high commodity prices. The standard income tax rate (reduced from 28% in April 2022 to 27% (PricewaterhouseCoopers, 2022)) for other commodities does not allow for this or protect the operations in times of low commodity prices.

1.1 Research Background and Context

The mining companies that the study focussed on are those operating mines that exploit the narrow, tabular mineral deposits that characterise the Witwatersrand gold mines of South Africa.

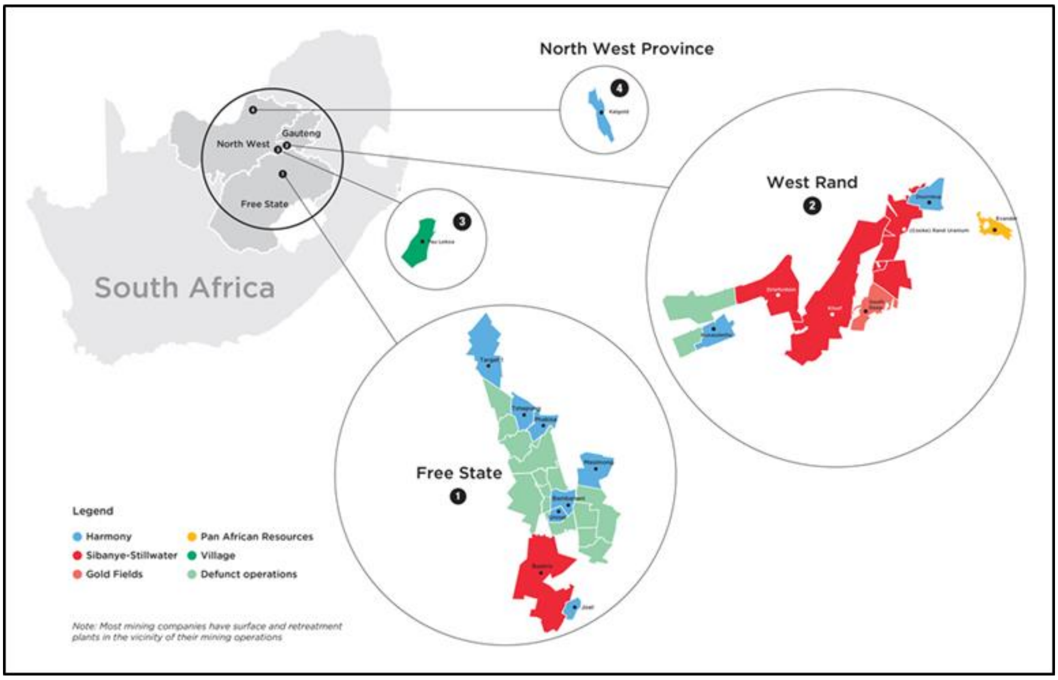

Figure 1-1. The Witwatersrand gold-producing areas in South Africa (Minerals Council South Africa, 2020).

Mining companies calculate a cut-off grade to determine the portion of the mineral deposit that can be mined economically. This cut-off grade considers the forecast price of the commodity, the expected mine recovery factor (MRF), the cost to mine the ore and extract the commodity, and the fixed costs for the mine. Using the planned extraction rate, expected recovery factor, total mineral extraction and sales costs, the variable element to break-even grade calculation becomes the in-situ grade of the sold material. The block will be mined profitably if the grade is higher than the break-even grade in a particular block.

Mining companies are approaching the question of mineral resource royalty costs and their impact on the cut-off grade in six possible ways. These are:

1. Ignore the implications and continue calculating the cut-off grade in the way it was done before the introduction of the tax;
2. Use the minimum rate (0.5% of total revenue (TR));
3. Estimate the expected rate that will be applied by looking at the historic rate;
4. Estimate the expected rate by modelling the optimised cash flow based on the break-even grade, and then determine the expected rate and use that as an additional cost for break-even grade calculations;
5. Assume that the highest rate will be applied depending on whether the mine is applying the refined (5%) or unrefined (7%) rate;
6. Use a profitability optimisation model, which applies a variable rate depending on the profitability, and determine if there is a higher profit to be made even if the profitability rate is lower.

1.2 Pay Limit and Cut-Off Grade

According to the South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves (the SAMREC Code), mineral reserves are that portion of the mineral resource that is valuable, legally, economically, and technically feasible to extract (Lomberg & Rupprecht, 2017). The commonly accepted method for determining if material forms part of the mineral reserve is thus to calculate the cut-off grade at the current economic conditions. In the absence of ore blending, only material above this grade is considered economic value and included in the mine plan. The material with a grade lower than the cut-off remains in the resource, although it may later be included in the mineral reserve with rising commodity prices or lower mining costs.

Storrar (1981: 145) has described, "*A pay limit is the minimum value at which ore can be mined and treated without profit or loss, that is when revenue obtained from the specific mineral product balances expenditure* *incurred in mining and treating the ore, and possibly, in transporting the marketable product to the delivery point."*

For gold mines in South Africa, the pay limit is calculated as follows:

Pay limit (pl):

$$pl = c \div p \qquad \text{Equation 1.}$$

Where: c is the cost in SA rand per tonne milled, and p is the price in SA rand per gram of gold. The pay limit is expressed in grams of metal per tonne of ore (g/t) (Cawood, 2011).

Lane (2016) stated that the boundary that distinguishes which material within a mineralised body is to be extracted and treated from the remainder is specified by the cut-off grade, which is, in effect, the economic definition of ore (Lane, 2016). The cut-off grade is the lowest value at which a specified mining unit may be mined profitably for the planning cycle under consideration. There needs to be a clear distinction between pay limit and cut-off grade because the two terms can sometimes be used interchangeably.

Pay limits are:

- Allows a ratio of un-pay mining to ensure the mill is filled (Storrar, 1981);
- Does not account for marginality; and
- As a result, they are higher than the cut-offs (School of Mining Engineering, 2021a).

A cut-off grade is:

- That value at which it is estimated that ore can be mined without profit or loss (Storrar, 1981);

- The economic boundary between ore and waste (Lane, 2016);
- The grade at which the mineral resource can no longer be processed at a profit (Hustralid, 2005);
- For material to be classified as ore, at a minimum, the extra return from the extra effort (to mine, mill, treat and market it) must exceed the extra costs incurred. The average costs have no bearing (Runge, 1988); and
- Cut-off grades are about marginality (School of Mining Engineering, 2021a).

What are the differences?

- Pay limits are applied on a global, average basis;
- Cut-off grades are applied to mining units;
- A cut-off is an absolute minimum;
- Cut-offs require detailed, accurate information;
- Cut-offs are dynamic in nature;
- Cut-offs relate to profits and value;
- Pay limits relate to Ore Reserve Mining Factors; and
- Cut-offs align with international practice (School of Mining Engineering, 2021a).

Taylor (1972) defines a cut-off grade *as "any grade that, for any specific reason, is used to separate two courses of action, e.g. to mine or to leave, to mill or to dump"* (Taylor, 1972, as cited in Bascetin & Nieto, 2007a). A cut-off is generally defined as the amount of metal a tonne of rock must contain to be sent to the processing plant (Rendu, 2008). This cut-off grade will change as metal prices fluctuate, the mine costs vary, and the project life stage that the mine is in (Lane, 2016).

The basics of the cut-off grade theory are described in Hall's *"Cut-off Grades and Optimising the Strategic Mine Plan"* (Hall, 2014). This book is a comprehensive study of the various techniques currently used in the mining industry. It includes multiple value measures, including optimising the discounted cash flow (DCF) and NPV (Hall, 2014).

The cut-off grade calculation is essentially straightforward. It determines the grade required for an ore unit to return a profit. It is essentially a break-even grade calculation where the volume is known (usually limited due to shaft capacity, mill capacity or some other physical constraint), and the unknown is the in-situ grade of the commodity. The derivation of the break-even cut-off grade formula (Equation 5) is presented in Chapter 4.

Optimising NPV can drive decision-making to focus on the short-term gains at the expense of the longer term, and thus companies often use the total undiscounted cash flow (Hall, 2014). The discount rate used to calculate the DCF and resultant NPV is critical to the cut-off grade calculation when calculated over the expected life of a mine.

This study's costs and income parameters are kept constant (real monetary value). For the initial study to justify this research project, 2015 values have been used (Birch, 2016a). 2021 cost and production values are used for the study presented in this thesis (Harmony, 2021a; Sibanye-Stillwater, 2022a). A real discount rate of 12% was used for the NPV optimiser model as this is near the upper limit for typical South African mining companies (Smith et al., 2007; Harmony, 2021b; Sibanye-Stillwater, 2021). This figure was chosen to emphasise the differences between the non-discounted cut-off grade and the NPV optimised cut-off grades and resultant mineable reserves. There is a more detailed review of how cut-off grades can be optimised in Chapter 4.

1.2.1 Resource Royalty and Income Tax Calculations

The State's two significant forms of direct revenue collection are considered in this study. These are the mineral resources royalty as well as income tax.

Mineral resource royalty

The introduction of the mineral resource royalty has increased costs as it is payable on the TR from the sale of the commodity, not just on the profits generated by the sales. This leads to increased mining risk because even if the mine makes a loss, there is still a payment due to the State due to this tax. The refined and unrefined formulae determine the South African mineral resource royalty rate. The State introduced the difference between the refined and unrefined rates to encourage the beneficiation of the commodities. When calculating the rate payable, these formulae consider the company's profitability, with highly profitable companies paying a higher rate (The South African Government, 2008).

The calculation of the mineral resource royalty is shown in Equations 2 and 3 (School of Mining Engineering, 2021b).

Refined Royalty Rate $(y(r))$

$$y(r) = 0.5 + (x \div 12.5) \qquad \text{Equation 2.}$$

Where: x is the earnings before interest and tax (EBIT)/(aggregate gross sales) ratio multiplied by 100 to express as a whole number, and $y(r)$ is the applicable tax rate. This rate is capped at 5%.

Unrefined Royalty Rate $(y(ur))$

$$y(ur) = 0.5 + (x \div 9) \qquad \text{Equation 3.}$$

Where: x is EBIT/(aggregate gross sales) ratio multiplied by 100 to express as a whole number, and $y(r)$ is the applicable tax rate. This rate is capped at 7%.

Capital costs (CapEx) related to the "win, recover and develop" of mineral resources are allowed to reduce the EBIT amount used in the royalty rate formula (The South African Government, 2008). These capital costs are as defined in Section 36 (11) of the Income Tax Act 58 of 1962 (The South African Government, 1962, 2008).

There is thus scope for optimising the cut-off grade by considering how these formulas vary with changes in profitability, especially when interacting with the South African gold tax described in Equation 4.

Income tax

The gold mining companies pay income tax based on the gold tax formula shown in Equation (4).

Income tax rate (gold tax) $(y\%)$

$$y(\%) = 34 - (170 \div x) \qquad \text{Equation 4.}$$

Where: x is the profit/revenue ratio multiplied by 100 to express as a whole number, and y is the applicable tax rate (School of Mining Engineering, 2021b).

The gold tax is only paid on the taxable profits of the mining company and excludes non-mining income (SARS, 2022) and is generally well understood by the various mining companies. The tax has an element of variation due to profitability, which is considered along with the mineral resource royalty when optimising the cut-off grade.

The Davis Tax Committee released its first interim report on mining taxes, and part of the recommendations made in the report is to review the gold tax formula. The committee has recommended that new gold mines be treated the same as other non-gold mining companies and subject to the corporate tax rate. Furthermore, gold mines are granted a CapEx allowance (12% of the unredeemed allowance) (Deloitte, 2015). Although the Davis Tax Committee has recommended retaining the gold mining formula for existing gold mines, changes to how mining companies are allowed to accelerate CapEx expenses have been recommended. Alternative to these suggestions, the committee has recommended that the gold tax formula be phased out over a reasonable period for all gold mines. This would account for neutrality when comparing new and existing gold mines (Deloitte, 2015).

A good tax should not disturb economic behaviour (Otto & Cordes, 2002; Mangondo, 2006). A primary objective of any business is to make a profit. Income tax is calculated on profits and does not alter business behaviour. The income tax can thus be considered neutral (Otto & Cordes, 2002). In general, mineral resource royalties are not considered neutral unless they are purely profit-based, and the royalty is allowed as a tax-deductible cost. The most common forms use the total mining revenue or the total ore extracted as a base upon which the royalty rate is applied. This then alters the cut-off grade calculation and influences the portion of the ore body that can be considered economically viable.

1.3 Problem Statement

The mineral resource royalty introduced in 2010 could affect reported mineral reserves in following the SAMREC Code. Due to it being paid on total mineral sale revenue, it must be considered an additional cost, despite being a deductible expense to calculate the income tax. During the initial research, it was found that mines typically base this cost on either the previous year’s royalty rate or estimate the rate based on their financial estimations for the new planning cycle. This approach then causes the break-even grade to increase and reduces the tonnes above this grade that can be economically mined.

1.4 Justification for Research

Each ore body is unique, and studies to establish the impact of the mineral resource royalty should consider ore body specifics rather than merely looking at industry-wide averages. The impact on some mines could be minimal, whilst others could be very significant. The results of a complete study should be considered in light of declining mining revenues and expected continuing job losses. The findings could guide future policy changes, such as those proposed in the SIMS document (ANC, 2012).

A cut-off grade model was developed for an initial study to determine the impact of discount rates on cut-off grades (*Impact of the South African mineral resource royalty on cut-off grades for narrow, tabular Witwatersrand gold deposits)*. The initial study to justify this Doctor of Philosophy (PhD) research topic was presented at the 23rd International Symposium on Mine Planning and Equipment Selection (MPES) in November 2015. This paper was published in the Journal of the Southern African Institute of Mining and Metallurgy (Birch, 2016a). The initial study focused on seven South African gold mines.

The initial study found that the gold mines researched include the expected cost of the mineral resource royalty in the cut-off grade calculation. This was accepted practice because this approach was followed by other mining countries where mineral resource royalties are applied. No consideration was given to the hybrid form of the South African mineral resource royalty formula (a combination of a minimum rate and a profitability aspect). The gold mines' income tax rate is also determined using a formula with a sliding rate based on profitability. Including the royalty costs following this approach increases the calculated cut-off grade. This reduces the mineable economic reserves and the mines' lives.

The South African gold mining industry has been a key catalyst for economic development. South Africa has declining Mineral Reserves due to having a mature industry and rising mining costs because of increasing depths and distances from the shafts. This has led to downscaling of the industry since the peak in the 1970s. From 2010 to 2020, production declined from 189 to 90 tonnes (Statista, 2022a). This decline is having significant consequences for the secondary cities which have been built on the back of the gold mining industry, for example, Matjhabeng (in the Free State province) and Matlosana (in the North-West Province) (Marais et al., 2017). The optimal cut-off grade to ensure that the Mineral Resource is fully exploited benefits the companies, and the State, provides critical jobs and allows the upliftment of communities.

1.5 Research Objectives

The primary objective is to understand the impact of the mineral resource royalty cost on the cut-off grade and identify the optimal approach for considering the costs to mitigate this impact. An Excel model (referred to as the “BirchOptimiser”) has been developed for the study. The development of this optimisation model is outlined in Chapter 5. During the initial research, the platinum mines do not apply the economic cut-off grade approach when planning their mining. They have, therefore, not been included in the development of the approach.

Consideration has been given to how cut-off grade calculations for gold mines consider the cost of capital and time-value of money. Comparisons are made between optimising for-profit compared to optimising for NPV. This also demonstrates how the selected discount rate changes the cut-off grades and impacts mineable resources and life.

The royalty costs are tax-deductible costs for determining the taxable income. This cost deduction reduces the profitability ratio used in the gold tax formula. Therefore, the royalty cost for gold mines reduces the taxable income and tax rate. The BirchOptimiser considers this interplay while determining the optimal cut-off grade for each approach under consideration (as identified in Chapter 1.1).

The BirchOptimiser developed to address the initial research question offers a very flexible approach to determining the cut-off grade. Because of this, two additional questions have been addressed. These are:

- Can some of the value lost due to grade estimation uncertainty be recovered by adjusting the cut-off grade?; and
- Can a multiple-criteria cut-off grade optimisation approach be developed considering distinct stakeholder groups in the mining industry?

The workings of the BirchOptimiser are explained in Appendix 1.

1.6 Research Methods

This study will include both qualitative and quantitative research methods.

1.6.1 Qualitative research

The general impact of mineral resource royalties on mining costs and the resultant cut-off grades are reviewed. A review of the South African MPRDA that introduced Mineral Resource Royalties to South African mines in 2010 was conducted (The South African Government, 2008). The purpose and intent of the MPRRA are considered, and consideration is given to who should benefit from the act. The other forms of revenue generated from the minerals industry are also considered (the indirect taxes).

The way mines consider the costs of the mineral resource royalty in their cut-off grade strategies is considered.

There is a review of the current cut-off grade optimisation strategies followed by the different mines. These include the following approaches:

- The break-even cut-off grade approach;
- The heuristic cut-off grade approach; and
- Lane's optimum cut-off grade approach (Githiria & Musingwini, 2019).

1.6.2 Quantitative research

A financial optimiser has been developed for quantitative research. This uses the Excel-based mixed-integer linear programming (Solver) function to optimise profit or NPV. These models all utilise real monetary value (excluding inflation and escalation) to reduce the uncertainties in assumptions regarding future costs and commodity prices.

The optimal approach to dealing with the costs associated with the mineral resource royalties is compared for a broad selection of South African gold mines to identify the most favourable approach. The six possible approaches are outlined in Chapter 1.1. The findings of this study are presented in Chapter 7.

The cut-off grade determined to maximise profit is compared to the one determined to maximise the NPV. These are compared to the purpose and intent of the MPRDA, and consideration will be given to a more holistic view of calculating cut-off grades.

Sustainable development and job creation/retention have become critical for mining in South Africa, and the State is expected to emphasise these aspects when awarding mining licenses. How mines can measure value beyond just the financial benefits will be considered. The optimisation model developed for this study allows a multiple-criteria optimisation approach to be followed.

The Decision Making Tools software suite by Palisade includes @Risk. This has been identified as a method to model the uncertainty found within the inputs to the cut-off grade calculations. @Risk is an add-on to Microsoft Excel that allows Monte Carlo simulations (Palisade, 2014).

Monte Carlo simulation produces distributions of possible outcome values from a set of assumptions by considering a probability distribution for each input. The probability distributions representing each input can be obtained in many ways, including historical values or estimations based on experience. These distributions have been used to simulate the block listings from published grade-tonnage curves for the various mines included in the study. The @Risk tools have also identified and simulated estimation grade uncertainties in the block listings. The financial optimisation created for this study is then used to consider how mines should adapt their cut-off grade strategies to consider this grade estimation uncertainty.

1.7 Sources of Data

For the initial impact of the mineral resource royalty study and the studies considering the optimisation of the NPV and grade estimation uncertainty, data from various mines have been used (Birch, 2016a,b, 2017). This data is not in the public domain, so the mines' names have been withheld. These studies are published in journal articles referred to in this thesis.

The information and data used for this thesis have been obtained from public domain sources. These sources are predominantly S&P Global Market Intelligence and the annual company Mineral Resource and Reserve reports. The names of these mines are stated in this study. Each ore body is unique, and the various mines are described, including their expected production profiles and cost estimates.

1.8 Research Validation

The initial study to justify this PhD research topic was presented at the 23rd International Symposium on Mine Planning and Equipment Selection (MPES) in November 2015. This paper was published in the Journal of the Southern African Institute of Mining and Metallurgy (Birch, 2016a).

A second publication (*Impact of discount rates on cut-off grades for narrow tabular gold deposits*) was presented at a Southern African Institute of Mining and Metallurgy conference in March 2015 to gauge peer acceptance of the methods employed. This conference paper was published in the Journal of the Southern African Institute of Mining and Metallurgy (Birch, 2016b). No negative comments were received following these initial presentations and publications; thus, the methodology is accepted.

Two additional research papers forming part of this PhD study have been published in peer-reviewed mining journals:

- *Optimization of cut-off grades considering grade uncertainty in narrow, tabular gold deposits* (Birch, 2017).
- *Review of cut-off grade optimisation from Southern African mines. Student assignment based observations* (Birch, 2018).

Furthermore, *Optimisation of mining block size for narrow tabular gold deposits* was presented at the 27th MPES International Symposium in 2018 (Santiago, Chile)(Birch, 2019).

1.9 Contribution to Knowledge

This study is envisaged to produce an optimised cut-off grade calculation approach that considers the sliding scale nature of the mineral resource royalty in tandem with the gold tax formula for typical narrow tabular gold mining operations in South Africa. The purpose is to mitigate the impact of the South African mineral resource royalty regime on tabular gold deposits through a new approach to cut-off grade optimisation. This method must be robust and straightforward to allow implementation by mining companies. Whilst there are other examples of using Excel Solver to optimise mining processes, a model to optimise cut-off grades similar to the one developed for this study has not been found.

The impact of the mineral resource royalty on the various mining companies' mineral resources is determined to see if the State is benefiting from this tax or whether the increase in cut-off grade is destroying more value than adding in revenue when considering other tax income streams. This thesis explores the interplay between the cut-off grade, average mining grade (AMG), royalty and gold tax and determines the optimal approach to consider the additional costs introduced by the royalties. The conventional thinking would consider that the additional costs introduced by the mineral resource royalties would increase mining costs and thus increase the cut-off grade, reducing the mine life. The profitability consideration in the mineral resource royalty formula allows mines to reduce the overall profitability and pay a lower rate for the mineral resource royalty and the income tax rate derived through the gold tax formula. Any reduction in cut-off grade is considered beneficial because it allows a greater proportion of the ore body to be mined, extending the life and providing the investors, state, mine employees and the wider mining community with an extended income. No similar study has been noted in the literature, and the benefits to the stakeholders for increasing the overall profit and revenue from the ore body are clear.

How mines should adjust their cut-off grades to consider grade estimation uncertainties is presented. Currently, the approach accepts each value to be correct. A cut-off grade optimisation approach considering this variability that is simple and robust for use by the mines has not been noted in the literature.

Determining how cut-off grade can be optimised considering a more holistic consideration of mining stakeholders using a multiple-criteria optimisation process approach to limit premature mine closure has been developed. The policy would need to be developed to encourage companies to use a more holistic approach for cut-off grade optimisation instead of focusing on profit or NPV. This is considered a novel approach and is considered New Knowledge.

The contribution to knowledge can be summarised as follows:

- The development of the BirchOptimiser;
- The development of a multiple-criteria cut-off grade optimisation approach;
- The development of an approach to consider grade estimation uncertainty in cut-off grade optimisation; and
- Identifying the optimal approach to mitigate the impact of the mineral resource royalty costs on cut-off grades.

1.10 Structure of the Research Report

This thesis consists of nine chapters. Chapter 1 is the introduction and covers the background of the research topic, the problem statement, the justification for the research, and the research objectives. The research methodologies followed by this study and the sources of the information are introduced. The research validation criteria, as well as the contribution to knowledge, are discussed.

Chapter 2 reviews mineral resource royalties and the implications for mineral resource management. The general forms of how mineral resources are determined are discussed. The South African fiscal regime is reviewed, including the mineral resource royalties and various mining income taxes.

South Africa’s mineral resource royalty costs are compared to other gold-producing countries in Chapter 3. The different royalty approaches followed by these countries are reviewed. The royalty cost implications for the various mining companies are presented along with a quantification of these costs compared with the overall mining costs.

Chapter 4 is a review of cut-off grade optimisation approaches. The broad approaches and how these have been developed over time are considered. There is a review of the methods commonly followed in the Southern African region. These various approaches are considered considering the requirements of this study and used as the basis for the optimisation model created for this study.

The break-even cut-off grade formulae and the Excel BirchOptimiser developed for this study are presented in Chapter 5. This includes descriptions of the block listing, ore flow and cash flow sheets used in the model. The Solver function is introduced, and its application in the optimisation approach is described.

Chapter 6 describes the mines included in the study. Their locations, as well as the ore bodies they are mining, are explained. The Measured and Indicated Mineral Resources obtained from the published mineral resource and reserve statements are presented. The grade-tonnage curves are considered, and simulated block models for each mine included in the study are created. The study's expected metal price, production rates, and cost data are determined in the analysis section.

The seventh chapter considers the six possible approaches for evaluating mineral resource royalty costs. The base case (identified from the initial research exercise (Birch, 2016a)) is compared to the other approaches to identify how mines should consider the royalty costs when determining the cut-off grade to optimise profit. The exercise also considers the optimal approach if $NPV_{12\%}$ is maximised (12% being the discount rate assumed for this exercise). This raises the question of which value should be optimised (profit, NPV, the life of the mine or revenue to the State) considering a broader spectrum of stakeholders in the mining industry. The study is based on 2021 values (costs and metal prices) and covers a far greater cross-section of South African gold mines than the initial study.

Chapter 8 focuses on the new knowledge developed as part of this study. Grade estimation uncertainty results in a loss of value. The BirchOptimiser is developed to identify how cut-off grades can be adjusted to recover some of this lost value. Finally, a multiple-criteria cut-off grade optimisation approach is proposed. Consideration is given to how a more holistic approach to the definition of value can be developed. This is considered unique because all the approaches reviewed in this study focus on maximising the output value as either the profit or NPV.

The final chapter summarises the overall results of the analysis and states the significant findings of the various studies. The research's contributions are highlighted, as are the research limitations. Finally, recommendations for further research are identified.

Three appendices are presented at the end of the thesis. Appendix 1 describes how the BirchOptimiser works and presents the various Excel formulae used. It also describes utilising the Excel Solver function to optimise the cut-off grade to maximise either the profit or the NPV. The modifications required to the BirchOptimiser are also described to optimise the cut-off grade whilst considering grade estimation uncertainty. Finally, the multi-criteria cut-off grade estimation approach is described.

Appendix 2 is the BirchOptimiser results of the study to determine the best approach to consider the mineral resource royalty cost in determining the cut-off grade. Appendix 3 is the results of the multiple-criteria cut-off grade approach.

2 REVIEW OF MINERAL RESOURCE ROYALTIES AND THE IMPLICATIONS FOR MINERAL RESOURCE MANAGEMENT

2.1 Introduction

Taxation is essential to non-renewable resource extraction (Lasserre, 1991). The in situ resource in South Africa is considered to be under public ownership. The country’s mineral resource royalty and tax regime are how the public will collect the rent owed to it from the users of the mineral resource (Lasserre, 1991). Mining investment decisions are impacted by the host country's taxation and social-environmental policies (Otto & Cordes, 2002). This section will consider the origins and forms of mineral resource royalties in the significant gold-producing countries. It will then focus on the South African MPRRA that introduced Mineral Resource Royalties to South African mines in 2010 (The South African Government, 2008). The origin of the South African mineral resource royalties lies in the MPRDA and the effective nationalism of the South African Mineral Resources (The South African Government, 2002). Furthermore, this section will consider the differences between income taxes and the various forms that mineral resource royalties can take. How these should be dealt with when considering mining costs for optimising cut-off grades will be considered in Chapter 4.

Lasserre (1991) considered the impact of taxes on mineral resource extraction considered the Ricardian world. In this model, the ore body is not considered homogeneous due to geological conditions (for example, the variable grade distributions in the South African narrow tabular gold deposits). As mining progresses, the mine’s depth and lateral extension increase, increasing costs. Extraction costs, therefore, are not independent of remaining stock reserves. They are expected to increase as stock reserves decrease. Mine planning could target the higher-grade areas early in a mine’s life to reduce the initial capital payback period, resulting in a progressively decreasing resource grade. The ultimate cumulative extraction depends on economic conditions, and closure occurs when a mine can no longer cover the extraction costs. Complete extraction would be assumed to be uneconomical (Lasserre, 1991). It is in the public interest that the maximum resource is extracted. This could conflict with the company's objective of maximising financial value (either measured as profit or NPV), which could consider an earlier exit preferable.

With the Ricardian theory of comparative advantage (Lasserre, 1991), countries’ mineral tax and royalty regimes add an additional layer of heterogeneity for investors to consider. Governments must consider the optimal level to set these rates to ensure investment and not miss out on rents (Cawood & Minnitt, 2002). Capital mobility has become common in the exploration and mining industry. This has resulted in very high competition for available investment capital between countries rich in mineral resources (Chatterjee, 2010). Cawood and Minnitt (2002) identify that investors, host governments, resource owners (if not publically owned), landowners, environmental groups and indigenous groups are all entitled to a portion of the rent from the exploitation of mineral resources. However, how this rent is distributed equitably is subject to unrealistic expectations and disagreements. A potential conflict may be considerably reduced if all legitimate beneficiaries are identified and the consensus is reached before mining commences (Cawood & Minnitt, 2002).

Mineral commodities are considered non-renewable. Hotelling, in 1931, argued that mines behave differently from other companies due to the exhaustible nature of their stocks. Reserves used today are not available in the future and could also lower the quality of the remaining ore (considering mines often exploit the highest grade ore early in a mines’ life to improve the NPV) (Tilton & Guzmán, 2016). There are thus fewer resources to exploit at a lower quality, leading to an increase in mining and processing costs in the future. Governments (South Africa included) encourage or impose regulations for mining companies to carry out downstream processing or purchase supplies locally (Tilton & Guzmán, 2016). This increases the costs for the mining companies, reducing profits (and taxable income) and increasing cut-off grades (reducing reserves). It is questioned if host countries should take the higher income taxes and use these to subsidise other industries more suited to the country's development goals (Tilton & Guzmán, 2016). How the profits of a mining company are distributed is subject to an ongoing debate. The revenue pie is finite and needs to be divided to satisfy the producer and host government (who effectively owns the mineral resource). If this is not attractive enough to the producer, there is no revenue to impose taxes on and no consumption of supplies (with the additional tax revenue) (Kesler & Simon, 2015).

Lilford (2017) considered the Australian situation and presented a gold case study where he reviewed the quantitative impacts of mineral royalties on mineral projects. He considered royalty rates of 2.5% and 7% and found reductions in the life of mine (LoM) of 0.5 and 1.25 years, respectively. Due to the 35% income tax imposed by the Western Australian State, he identified that the loss due to the reduced earnings would be A$81 million over the shortened life scenario. Furthermore, the State would then be liable to pay the retrenched workers welfare amounts, assuming they could not immediately find replacement employment. He determined that overall, the loss to the State would amount to A$19.2 if a 2.5% and A$46.2 million if a 7% royalty were imposed, respectively. He concluded that the imposition of the royalties could not be justified economically and that the State would be disadvantaged in the long term (Lilford, 2017). This study by Lilford confirmed the approach followed in the methodology for this research project in that any proposed changes to mineral tax and royalty charges need to start with the impact on the ore body. According to the previous Harmony chief executive officer, Bernard Swanepoel, "*the ore body dictates*" (Boshoff, 2016).

The mining industry is considered unique compared to traditional businesses, and various arguments are put forward as to why the industry should receive special treatment when it comes to taxation (Otto & Cordes, 2002; Otto et al., 2006). These include the following:

- Mineral exploration required to discover economically viable deposits is lengthy and very risky. There is no revenue generated during this process.
- Extensive capital is required to develop a mine, and the development time can be very long. The repayment of the initial capital could be many years, exposing the investors to significant market risk. This is because the economics of the mine when production starts could be very different from when the feasibility studies occurred.
- The capital invested into the project is captive, most of which is in the form of mine development. This capital cannot be recovered if the project fails.
- Specialised equipment is often required. Only a few manufacturers supply this equipment, often requiring it to be imported into the country where the project is based.
- The long lives of mines mean they are subject to commodity price cycles and even regime changes over the LoM.
- On closure, extensive rehabilitation costs could be required, and provision for this must be made over the project’s lifetime.
- Mines are often subject to substantial additional costs unrelated to the core production costs. These include social upliftment and infrastructure programs (Otto et al., 2006).

The mineral deposits that mines exploit are non-renewable resources. In most countries, mineral resources are considered to belong to the state (Otto et al., 2006). Massive pressure is often brought on mining companies that the public needs to benefit from the mines. Mines must not be enriching themselves at the expense of public benefit (Otto et al., 2006). Mining companies' corporate social responsibility activities are considered to have limited benefits when it comes to poverty alleviation (Gamu, Le Billon & Spiegel, 2015), so strong governance is required. There is often an ambiguous relationship between a country's extractive industries and development, where countries endowed with ample mineral resources lag behind those with limited resources (Gamu, Le Billon & Spiegel, 2015). This is termed Dutch disease (Kolstad & Søreide, 2009; Tilton & Guzmán, 2016; Ebrahimzadeh, 2020).

Numerous forms of royalties, taxes and levies benefit the state. For South Africa, for example, these include but are not limited to the following:

- The mineral resource royalty (already introduced as the key subject of this thesis and will be discussed in more detail in this section);
- Income tax (the corporate rate is currently 27%, but gold mines pay on a sliding scale (the gold tax formula) which has been discussed previously;
- Employees' income tax;
- Dividends tax;
- VAT;
- Social and labour plan contributions;
- Skills development levy; and
- Excise duties and levies, including the fuel levy (The South African Revenue Service, 2021).

For this research project, the mineral resource royalty and income tax will be considered direct taxes. The company will collect employees' income tax but consider it separately from the direct tax paid by the company. Because all of the gold produced is considered to be exported, all VAT costs on supplies and services can be recovered (Ralbovsky & Symons, 2010). Taxes borne will include un-recoverable VAT, social and labour plan contributions, the skills development levy and the various excise duties and levies, and the taxes the suppliers would have paid on their income (Ralbovsky & Symons, 2010). Whilst the direct taxes can be determined through the calculations in the analysis part of this thesis, indirect taxes (excluding the dividends tax) can be estimated as a proportion of the mining costs. Cawood (2011) estimated that in 2009, 25% of tax revenue came from direct company income taxes, 30% from personal income tax and the balance from these other revenue streams. This fits in with Grobler (2014), who estimated that personal income taxes contribute approximately 30% of the total tax revenue generated by a company. Corporate income taxes contribute between 20% to 25%, whilst the balance comprises other taxes (approximately 45% to 50%) (Grobler, 2014).

Cawood and Minnitt (2002) considered how the rent from a mining project should be shared. He estimated that the State's share of the wealth should be approximately 35% for South African mining projects. The resource owner should receive an additional 4.7%. Considering that, following the introduction of the MPRDA in 2002 and the MPRRA in 2008, the State is effectively the resource owner and receives the mineral resource royalty, this would bring the State's share of the wealth to 40% (Cawood & Minnitt, 2002).

A study by PricewaterhouseCoopers (PwC) in 2010 considered the total tax contribution made by mining companies across several regions. This study included Africa and determined that corporate income tax represents 17% of the total taxes. Mining taxes, royalties and other contributions account for 31%, whilst production and property taxes account for 44%. Employees' income taxes (income tax paid by mining employees) account for 8%, which is far lower than the contribution made in other regions (16% in Latin America and 36% in the high-income Organisation for Economic Co-operation and Development (OECD) countries) (Ralbovsky & Symons, 2010). This study identified that during full production, mines contribute:

- Employees' payroll taxes as well as social contributions;
- Indirect taxes;
- Taxes paid by suppliers;

- Royalties; and
- Taxes on profit.

For Africa, the total tax rate (as a percentage of total turnover) is estimated to be 11.3%. This is split between 7.5% for taxes and contributions borne and 3.8% for taxes collected (Ralbovsky & Symons, 2010). The study found that for every $1 of corporate income tax, mining companies contribute an additional $1.50 in other taxes and contributions, plus $0.52 in taxes collected. Corporate income tax is, on average, 40% of all taxes and contributions made by mining companies (Ralbovsky & Symons, 2010).

2.2 General Forms of Mineral Resource Royalties

A royalty is a payment made to the sovereign owner of the resource for the right to exploit the minerals (Otto et al., 2006). Most countries impose some form of royalties. Some countries did not traditionally charge a royalty and have only introduced these in the last decade (for example, South Africa and Mexico). Before the MPRDA, royalties were paid to the private mineral rights owner rather than the State in South Africa. If the State was the mineral rights holder, they determined and collected the royalty (Cawood & Minnitt, 1998). It should be recognised that there is some optimal taxation level. If the rates are too high, investors will not invest in a country's mineral resources, so the country will lose the benefits of exploiting those resources. If it is too low, the country will only derive the non-tax benefits to the detriment of its fiscus.

The exploitation of mineral resources often impacts other areas of the economy, such as tourism and agriculture (Field-Humby, 2019). These need to be balanced against mineral wealth, and the country should seek an equitable balance between the various sectors of the economy. Otto et al. (2006) have identified that determining the optimal level of taxation is not easy in practice. It requires knowledge of how a company's behaviour will be altered to respond to changes in taxation policies (Otto et al., 2006). One of the early criticisms of this study is that the research focuses on how the various companies will alter the cut-off grade in response to the South African Mineral Resource Royalty. However, this is understandable because mines are businesses, and any business's primary focus is the shareholders' benefit.

Mineral royalties are generally applied in four ways (Otto et al., 2006):

- A unit-based royalty, which is a tax based purely on the amount of the mineral produced;
- *Ad valorem* royalties are based on the amount produced and the value of the mineral. Unlike unit-based royalties, *ad valorem* royalties fluctuate according to the commodity price;
- Profit-based royalties allow for a broader range of costs to be deducted, including capital costs; and
- Hybrid royalties, i.e. a combination of the above.

Economists are critical of volume-based royalties (for example, on every tonne of ore mined) because they add to the production costs. This could make low-grade ore uneconomical to mine profitably (Otto et al., 2006), and it will be sterilised. In this case, tax on profits is more efficient because it will not alter whether to mine marginal ore. These profitability-based taxes and royalties distribute the risk between the State and the company.

Otto et al. (2006) noted that unit-based and *ad valorem* type royalties are generally dominant when considering the various mining jurisdictions. This is also noted when reviewing the royalty costs in the top ten gold mining countries covered in Chapter 3. Profit-based royalties are thought to be less economically disruptive, so the predominance of unit-based and *ad valorem* types is considered questionable (Otto et al., 2006). Profit-based royalties, however, introduce the following problems:

- The determination of profit can be challenging to administer, and ambiguities lead to difficulties in determining the correct profit value (which is usually different from the profit used to determine the corporate income tax);
- Profits need to be determined at a project rather than the corporate level, which raises questions as to what could be considered legitimate deductions to allocate back to the project;
- The public often suspects that the lack of profitability is due to company incompetence or, in the case of multinational companies, the export of profits to other tax domains (termed tax base erosion and profit shifting) (Guj et al., 2017; Cobham & Janský, 2018; Field-Humby, 2019); and
- Governments are thus exposed to:
  - Commodity price cycles affect the profitability of the projects and thus the revenue stability; and
  - Project risk is inherent to the different mineral projects (Otto et al., 2006).

There could, thus, be times when the State receives no revenue even though the mineral resource is being depleted (Otto et al., 2006; Field-Humby, 2019). A compromise to this is adopting a hybrid, profit-based royalty with a minimum rate or *ad valorem*, ensuring a revenue stream to the State even if the project makes a financial loss. South Africa has introduced this form of royalty, but other examples are found, for example, the royalties applied to rough diamonds and vanadium pentoxide in Western Australia (Otto et al., 2006)

Another form of royalty model is resource rents. The rationale for linking taxation to rents is that the owners of the company are fairly compensated for the production (including their capital and expertise), and yet the public (represented by the State) is allowed a fair return on the depletion of a national asset (Otto & Cordes, 2002). These represent the surplus revenues from a mineral deposit after deducting mining-related costs (exploration, development and extraction) (Otto & Cordes, 2002). An acceptable return of capital is also allowed, including risk-free and a risk premium component (Parliamentary Monitoring Group, 2013). Australia introduced a mineral resource rent tax (MRRT) in 2012 for coal and iron ore profits. There are advantages and disadvantages when comparing mineral royalties to resource rent taxes (Parliamentary Monitoring Group, 2013). These are as follows:

Mineral royalties

- Advantages
  - Over-extraction of resources is inhibited;
  - Yields revenue from the start of production;
  - Revenue is stable; and
  - Lower administration and compliance costs.
- Disadvantages
  - Can lead to high grading;
  - Extraction can be timed to lower royalty payments;
  - Only a portion of the mining rents is recovered when the commodity prices are high, and operations are also taxed when no economic rent is present (low commodity prices when the operation is running at a loss).

Resource Rent taxes

- Advantages
  - Windfall gains are targeted.
- Disadvantage
  - Only imposed when profits are abnormally high, and no income when profits are low (dependent on the commodity price cycles);
  - This leads to revenue dependent on the commodity price cycles;
  - Not very efficient as it targets a narrow tax base with high tax rates;

- It is difficult to define an appropriate tax base; and
- It is administratively complex (Parliamentary Monitoring Group, 2013).

2.3 South Africa's Mining Fiscal Regime

South Africa's mineral fiscal regime is simply the package of taxes imposed on mining activities in the country. All countries tax mining differently, but in general, they have the following three categories of taxes to work with:

- Tax on mining inputs and outputs;
- Tax on production; and
- Income tax.

2.3.1 Tax on mining inputs and outputs

South Africa is very generous regarding taxation on mining inputs and outputs (Curtis, 2009). Mining companies can deduct capital expenditure against income tax, including spending on prospecting, mining equipment and shaft sinking, development, general administration and management before the commencement of production. This amount can also be increased in gold mines by 12% on the unredeemed balance annually as a capital allowance reducing income tax. Mining companies can carry forward any losses indefinitely and set these against future profits. There are no restrictions on the repatriation of profits. VAT is applied at the standard rate of 15%, but exports are zero-rated. Considering that most of the gold mines subject to this study are exported, this is important because these companies can claim a VAT refund for all input taxes (Curtis, 2009).

2.3.2 Tax on production

These are charges applied to the actual output of the mine and consist of all taxes that enterprises incur because of engaging in production, independent of the quantity or value of the goods and services produced or sold. The taxes on production mainly comprise the payroll tax, compensatory payments related to transport, the territorial economic contribution, and taxes on land and buildings (Insee, 2021).

2.3.3 Tax on income

Like other industries, mining companies pay corporate income tax, which taxes their taxable income. As amended, the Income Tax Act No. 58 of 1962, South African Revenue Service Act No. 34 of 1997 and Tax Administration Act 2011 regulate the South African tax regime (Curtis, 2009). For all mineral resource projects, except gold and uranium, the corporate income tax rate is 27% (from 28% in April 2022 (PricewaterhouseCoopers, 2022)). Gold mines' taxable income is derived from a formula accounting for the ratio of profits to revenues. As the profitability rises, the State takes a more significant proportion in tax. If the company makes no profits (or low profits at around 5% of revenues), the State receives no tax (Curtis, 2009). However, the marginal tax rate is 34% for highly profitable gold miners, which means they could pay a higher income tax rate than other miners or corporations in South Africa.

This gold tax sliding scale is vital for this study because the mineral resource royalty is considered a tax-deductible cost, reducing the income tax payable (Curtis, 2009).

Mine employee salaries are also taxed. The sliding scale for personal income tax starts at ZAR91,250 per annum with an entry-level tax rate of 18% (South African Revenue Service, 2022). The maximum rate is 45% (South African Revenue Service, 2022). The average South African semi-skilled mine employee’s salary would fit into the lower two tax scales (Talent.com, 2022), with the supervisors and management entering the upper scales.

2.4 Mineral and Petroleum Resources Development Act, 2002

"To make provision for equitable access to and sustainable development of the nation's mineral and petroleum resources; and to provide for matters connected therewith." (The South African Government, 2002).

The purpose of the MPRDA is to recognise that the country's non-renewable mineral resources are under the custodianship of the State, and the benefit of the wealth must not be discriminatory. Furthermore, the act aims to protect the environment through sustainable mining practices and ensure economic and social development (The South African Government, 2002). The act thus recognises that previously the South African mineral wealth was not distributed equally amongst the country's citizens due to racial discrimination.

The Objects of the MPRDA (Section 2) identify that the State has the sovereign right over all mineral and petroleum resources in the Republic of South Africa (Section 2(a)). The act was written to promote equitable access to mineral wealth for all people of South Africa (Section 2(c)) as well as promote economic growth (Section 2(e)). Section 2(f) states, "*promote the employment and advance the social and economic welfare of all South Africans*". The MPRDA gives effect to Section 24 of the Constitution of South Africa, which requires "*that the nation's mineral and petroleum resources are developed in an orderly and ecologically sustainable manner while promoting justifiable social and economic development*" (Section 2(h)) (The South African Government, 2002).

Section 51 of the MPRDA considers the optimal mining of mineral resources. The Board (The Minerals and Mining Development Board as established by Section 57) may recommend to the Minister to direct the holder of a mining right to take corrective measures if the Board shows that the minerals are not being mined optimally or that continuation of such practice will detrimentally affect the objects referred to in Section 2(f) (The

South African Government, 2002). The optimisation of cut-off grades thus needs to consider the multiple stakeholders (in this case, all South Africans) rather than just the mining company's shareholders.

2.5 Mineral and Petroleum Resources Royalty Act, 2008.

"A person that wins or recovers a mineral resource from within the Republic must pay a royalty for the benefit of the National Revenue Fund in respect of the transfer of that mineral resource." (The South African Government, 2008)

Before the MPRRA, mining companies were not required to pay any form of royalty to the State (unless mining state-owned land). Mineral rights were privately owned and were registered with the South African Deeds Office as immovable property (Cawood & Macfarlane, 2003; Grobler, 2014). If the mineral rights owner chose not to sell the mineral rights to a mining company, any royalties were paid to the rights owner. These payments were negotiated between the owner of the rights and the mining company, and the State was not entitled to any form of compensation from these contracts (Cawood & Macfarlane, 2003; Grobler, 2014). If the mining company bought the mineral rights from the mineral rights owner, no mineral royalties would be paid over the mining project's life. In the case where the State owned the mineral rights, mineral lease agreements were entered between the mining company and the State, and the State would then receive the mineral royalties (Grobler, 2014). The MPRRA replaces the previously negotiated contracts.

The current tax legislation will be used to source the present formulas for calculating the taxes payable by mining companies. These include the MPRRA (The South African Government, 2008) and the Guide for Tax Rates/Duties/Levies (The South African Revenue Service, 2019). An Explanatory Memorandum for the Mineral and Petroleum Resources

Royalty Bill, 2008 (Payne, 2008) is also utilised for clarity. *The South African mineral and petroleum resources royalty act – Background and fundamental principles* (Cawood, 2010) discuss some of the backgrounds of how the mineral resource royalty was established. It also covers some of the principles and issues likely to arise from its implementation.

Mangondo (2006) looked at the benefits of profitability-based income tax for mining (as utilised for gold mines) compared to flat tax income tax for other commodities. He also reviewed the mineral resource royalty as a replacement for income tax rather than having a two-tiered taxation system (Mangondo, 2006).

Mining Royalties. A Global Study of Their Impact on Investors, Government, and Civil Society (Otto et al., 2006), investigates Mining Royalties' impact on mining projects worldwide. This will be used to compare the recently introduced South African Mining Royalties Tax with what is being applied elsewhere in the world and look at alternative taxation structures that may be applied in the future. The effects of changing tax law have been documented in Canada (DeYoung, 1977), specifically the impact of resource royalties' type taxation (Power & Jewkes, 1991).

Cawood (1999) completed a PhD in determining the optimal rent for South African mineral resources. In this study, the need to encourage investment is balanced with the requirements of countries to benefit from their mineral wealth and proposes a formula to calculate these payments. This study is based on extensive research of royalties across the globe to guide the development of the formula. Any royalty should be simple to administer and unambiguous in calculating the payment required (Cawood, 1999). Cawood has also investigated the potential impact of the new South African Mineral and Petroleum Resource Royalty Act (Cawood, 2011), identified that marginal mines could be negatively impacted, and the need for further research into this aspect.

Oshokoya (2012), in her master's report (*The new South African mineral royalty formulae. Will all miners become refiners? Platinum case study*), reviewed the current resource royalty and looked at how successful the royalty formula is regarding its encouragement of further downstream beneficiation within the platinum industry. As it currently stands, the royalty has different rates for refined and unrefined products. It has been written to encourage companies to further beneficiate their products if this is now not the case (Oshokoya, 2012).

Oshokoya has subsequently researched what improvements should be introduced to the South African mining royalty to encourage optimal mineral use to increase the benefit of the citizens of South Africa. This benefit will not be derived by increasing the amount payable but by having a mineral royalty regime that encourages industry investment and growth and downstream beneficiation and value-add through further industrialisation (Cawood & Oshokoya, 2013; Akinseye & Cawood, 2021).

The ANC has indicated that it feels that in times of commodity price upswings, the State should be allowed a more significant portion of the profits ("super tax or windfall tax") (ANC, 2012). The ANC feels that the resource royalties tax in its current form is not achieving this. The SIMS document (released in June 2012) has called for reviews of how the State receives revenue from the mining sector (Parliamentary Monitoring Group, 2013). There could thus be changes in the future in how the mineral resource royalty is structured. However, this study focuses on the current tax and how it guides mining and investment decisions.

The first interim report on mining prepared for the Minister of Finance by the Davis Tax Committee released in June 2015 has reviewed the current tax regime. The committee has recommended that the mineral resource royalty not be altered or replaced by some super profit tax (as suggested in the ANC Sims document (ANC, 2012). The Davis Tax Committee has considered the differences in gold mine taxation compared to other mineral commodities and suggested that alterations for new gold mines could benefit the State (The Davis Tax Committee, 2016).

2.6 Chapter Summary

The South African mineral resource royalty introduced in 2010 (per the MPRRA) is applied in a hybrid *ad valorem* way. This chapter has presented an overview of general mining royalties and the other forms of taxation prevalent in the South African mining industry.

It must be recognised that the additional revenue states generate from imposing royalties could be detrimental. These effects include opportunity loss as a consequence of:

- Shorter LoM, which results in reduced employment opportunities and the impact of this on local communities;
- Reduced income taxes over the life of the mine as well as from the mine employees;
- Higher welfare costs due to the rise in unemployment when the mine closes; and
- Permanent resource sterilisation (Lilford, 2017).

Chapter 3 will present how mineral resource royalties are determined in the significant gold-producing countries. These approaches are then compared to the South African mineral resource royalty regarding the cost implications when considering the cut-off grade approach.

3 OVERVIEW OF THE MINERAL RESOURCE ROYALTY APPROACH AND MINING COST IMPLICATIONS OF ROYALTIES IN THE TOP TEN GOLD-PRODUCING COUNTRIES

3.1 Introduction

The significant gold-producing countries have different approaches to collecting royalty revenue from their mineral assets. This chapter reviews the various royalty methods commonly used by the major producers and then determines the cost impact of these royalties on the overall mining costs. When considering how costs are included in the cut-off grade calculation, how these are determined is considered essential. The royalty formula used for South Africa is a hybrid *ad valorem* approach. The approaches utilised by the other significant gold-producing countries are reviewed to see how they differ from the South African approach.

The figures presented in this section are obtained from the S&P Capital IQ Pro Platform. This is a subscription platform where company information is presented in a standard format (S&P Global, 2022). The figures used for the costs are the total cash cost (TCC). This is considered the most helpful measure of short-term profitability for a mine site (S&P Global, 2021). The following costs are included:

- Mine labour (including salaries and additional costs allocated to the mining workforce);
- Mine fuel (petrochemical fuel);
- Mine electricity (including grid as well as the petrochemical costs for own-power generation);
- Other mine costs (stores and services);
- Mill labour (including salaries and additional costs allocated to the processing plant workforce);
- Mill reagents (chemicals and consumables);

- Mill electricity (including grid as well as the petrochemical costs for own-power generation);
- Other mill costs (stores and services);
- Transport and offsite (transport of final product to the final destination as per the agreement with clients);
- Smelting and refining (smelting and treatment to the final product);
- By-product credit (any credit income from by-products); and
- Royalty and production taxes (all royalty and 'front end' taxes applicable to production) (S&P Global, 2021).

The royalty costs include unit-based royalties where the base is a physical unit, *ad valorem* royalties based on the value of production, profit-based royalties where these are calculated for the mine output itself, and economic rents (S&P Global, 2021). The TCC figures are presented as US$/oz paid metal-produced costs.

These TCC figures exclude corporate overheads, reclamation and closure provisions, exploration and other sustaining costs, and sustaining CapEx. These costs are included in the all-in-sustaining cost (AISC) figures (S&P Global, 2021). Corporate income tax, depreciation, non-sustaining CapEx, interest charges, extraordinary charges (for example, strike costs or unexpected closure costs) and all other costs not related to the current are excluded from the TCC and the AISC (S&P Global, 2021).

3.2 Countries Selected for the Study

The following ten countries have been identified as the world's significant gold-producing countries for 2021. They were selected based on S&P Global Market Intelligence gold production values (S&P Global, 2022):

- Australia;
- Burkina Faso;
- Canada;

- China;
- Ghana;
- Mexico;
- Russia;
- South Africa;
- United States; and
- Uzbekistan.

Mines, where gold is not the primary product, have been excluded because some countries have different commodity royalty regimes. The graphs are presented following the logic found in cost curves. The lowest-cost producer is on the left, with the countries/companies ordered according to the overall mining costs. The highest-cost producer is on the right. This allows the observation of the royalty costs (with the countries/companies in the same order as the total mining cost graphs) to identify if there is a similar trend noted with these costs. Graphs are only presented for countries or regions with two or more mines.

Figure 3-1 shows the royalty costs compared to the overall costs (mining, milling, treatment and refining) for the significant gold-producing countries. Figure 3-2 shows the royalty charges (US$/oz), and 3-3 shows the percentage of royalty charges compared to the total cost.

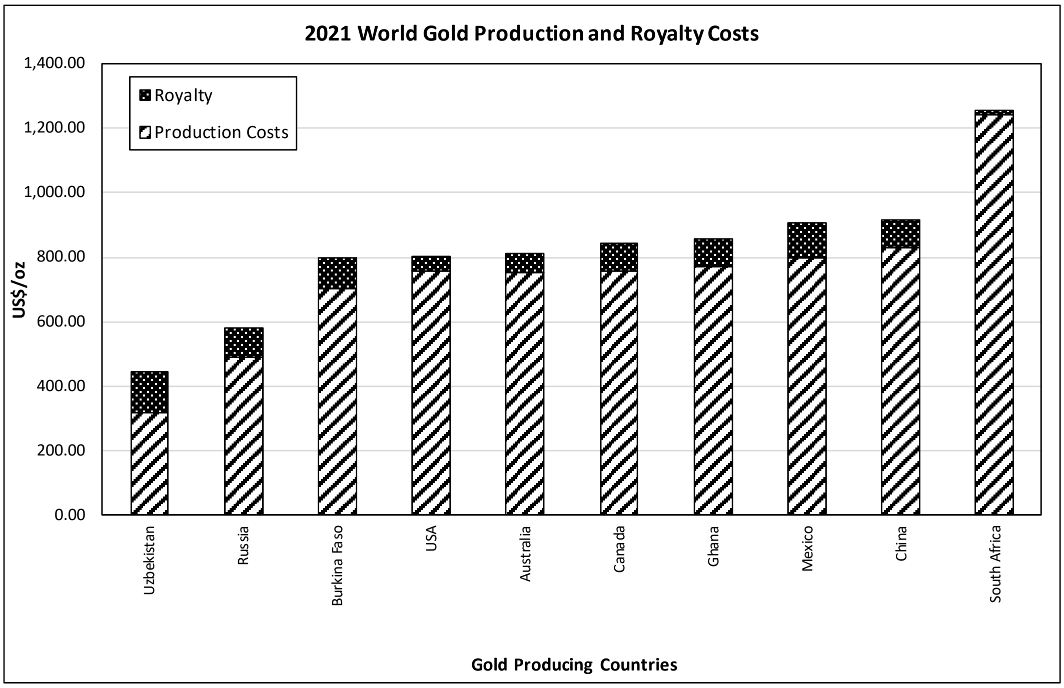

Figure 3-1. The royalty as a proportion of the total mining costs for the significant gold-producing countries (S&P Capital IQ, 2021).

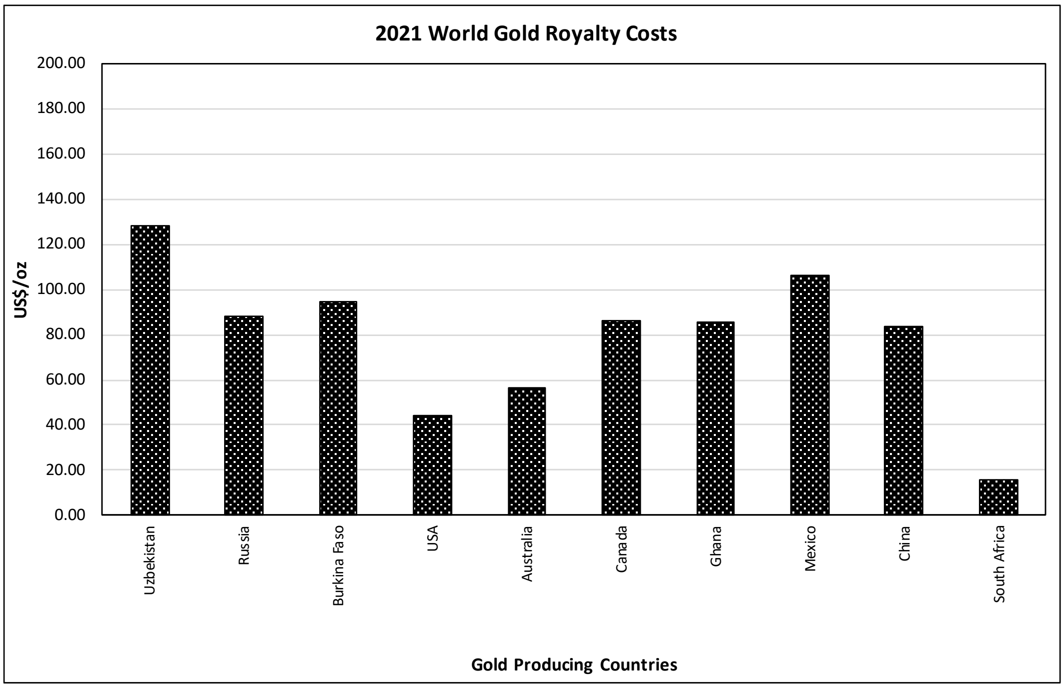

Figure 3-2. The royalty costs for the significant gold-producing countries (S&P Capital IQ, 2021).

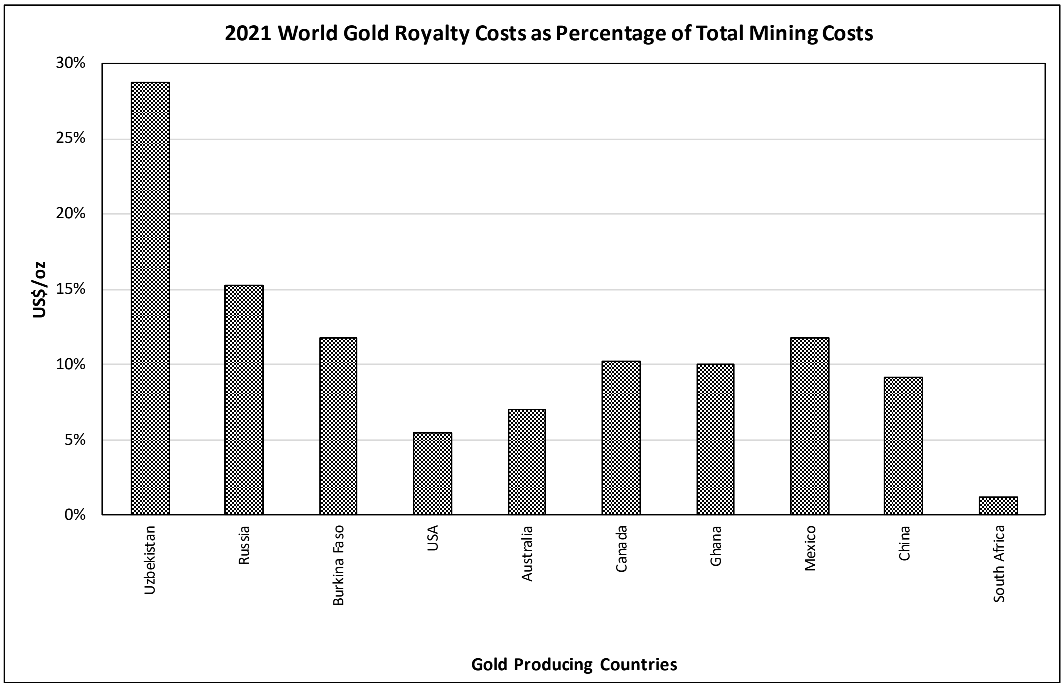

Figure 3-3. The royalty as a percentage of the total mining costs for the significant gold-producing countries (S&P Capital IQ, 2021).

It can be seen in Figure 3-1 that Uzbekistan has the lowest overall gold production costs (US$447/oz), whilst South Africa has the highest (US$1,257/oz). Figure 3-2 shows the royalty costs (US$/oz), which range between US$15/oz (South Africa) and US$128/oz (Uzbekistan). It can be observed in Figures 3-3 that South Africa has the lowest royalty charges of any of the significant gold-producing countries when expressed as a percentage of the total US$/oz cost (1.2%). For most other significant gold-producing countries, the royalty costs represent 5% to 15% of the total mining costs, except Uzbekistan, which is noted to be 29%.

3.2.1 Australia

Each state in Australia has its system of royalties. These are very complex and detailed, with each commodity and state subject to different rates. Figures 3-4 and 3-5 show the royalty as a portion of the total costs of the various Australian gold mining companies and the royalty costs.

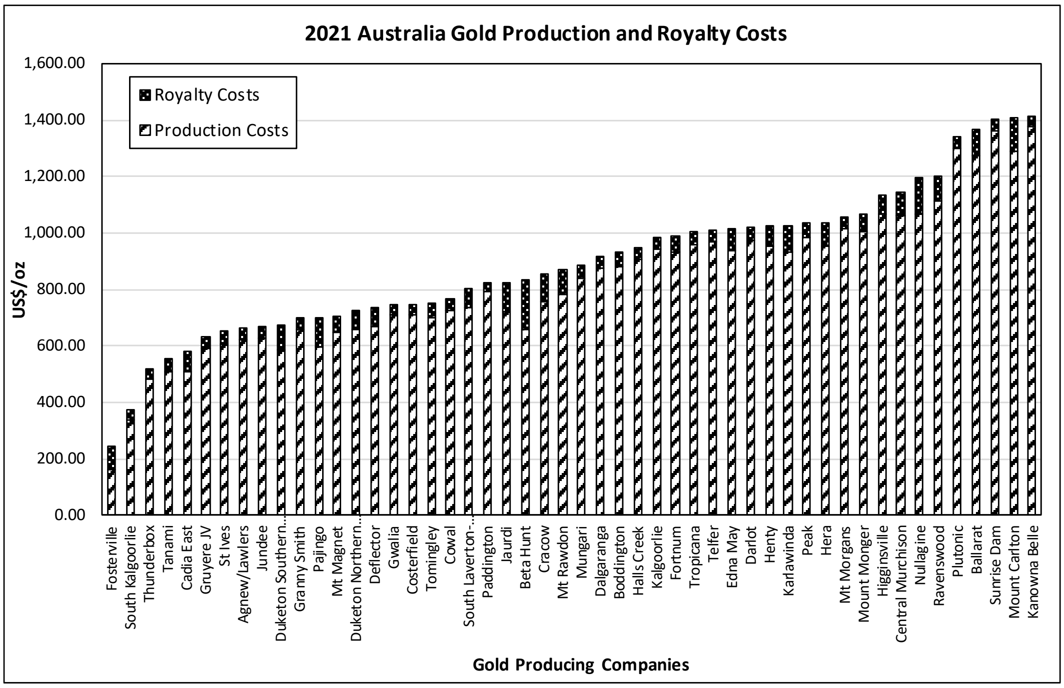

Figure 3-4. Australian primary gold mining companies' costs with the royalty portion indicated (S&P Capital IQ, 2021).

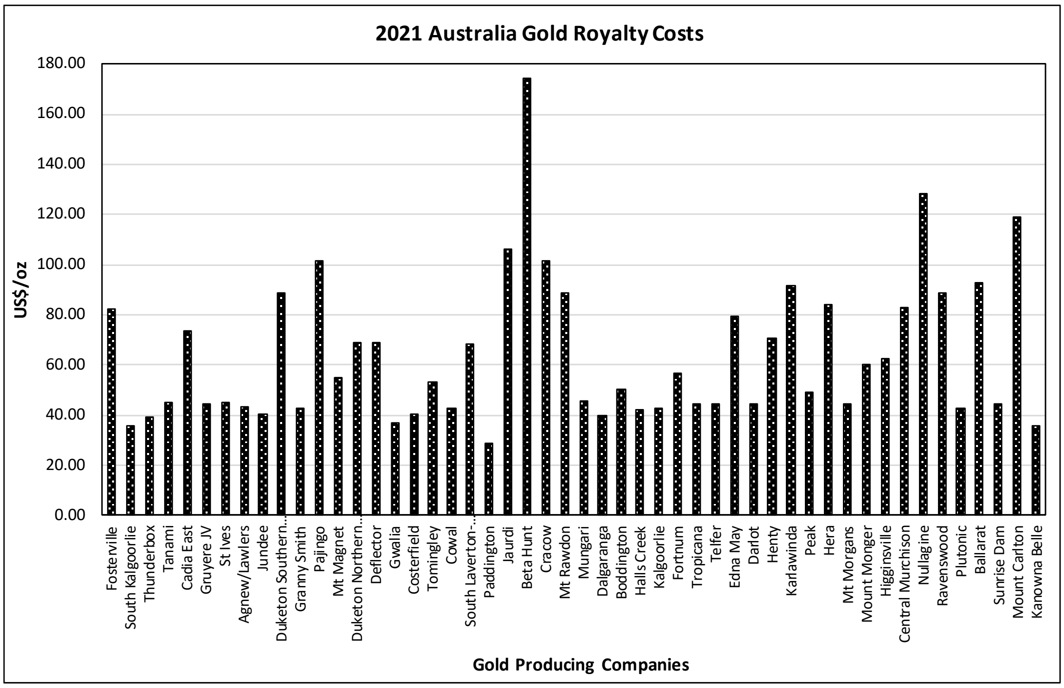

Figure 3-5. The royalty costs for the Australian primary gold-producing companies (S&P Capital IQ, 2021).

It is noted that the royalty costs range from US$28/oz to US$174/oz (the average being US$57/oz). The royalties average 7% of the total mining cost, ranging from 3% to 34%.

Most royalties are unit or *ad valorem* based. The Western Australia royalty is 2.5% of invoice value minus deductions such as transport value (Otto et al., 2006). Western Australia has imposed higher royalties on raw products than products with value-added (metals). This is to encourage local processing (Otto et al., 2006). Figures 3-6 and 3-7 show the royalty as a portion of the total costs and the royalty costs (US$/oz) for the various Western Australian primary gold mining companies.

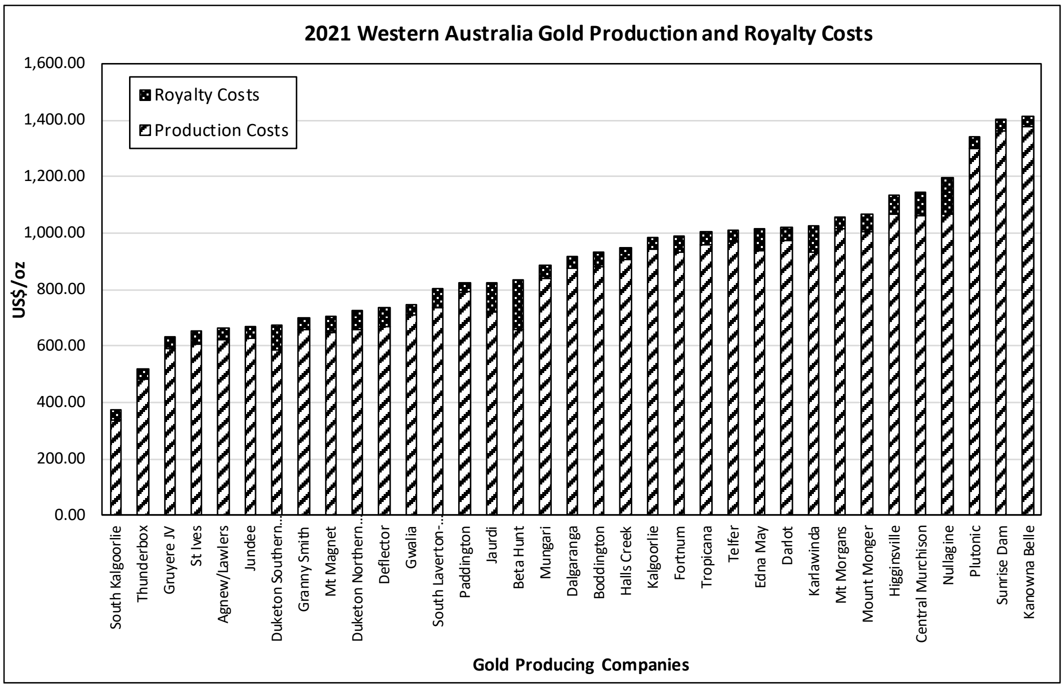

Figure 3-6. Western Australian gold mining companies' mining costs with the royalty portion indicated (S&P Capital IQ, 2021).

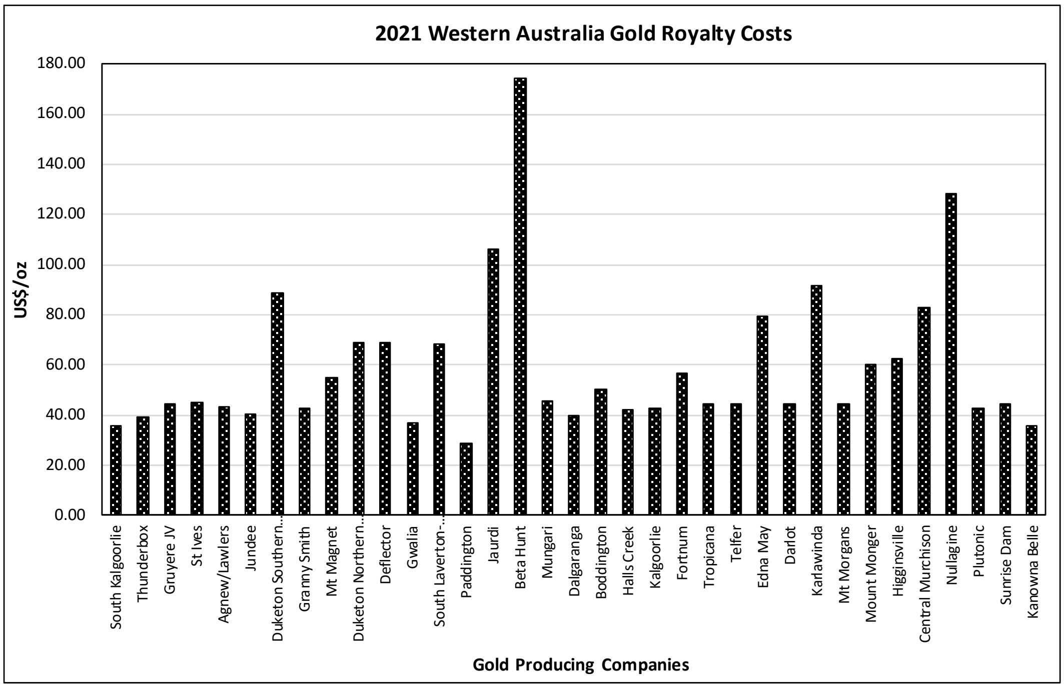

Figure 3-7. Western Australian gold mining companies' costs with the royalty portion indicated (S&P Capital IQ, 2021).

It is noted that the royalty costs range from US$36/oz to US$91/oz. The average cost is US$50/oz. The royalty costs represent 3% to 10% of the total mining costs.

New South Wales imposes a 4% *ad valorem* on the value minus allowable deductions for gold. Figures 3-8 and 3-9 show the royalty as a portion of the total and royalty costs (US$/oz) for the various New South Wales primary gold mining companies.

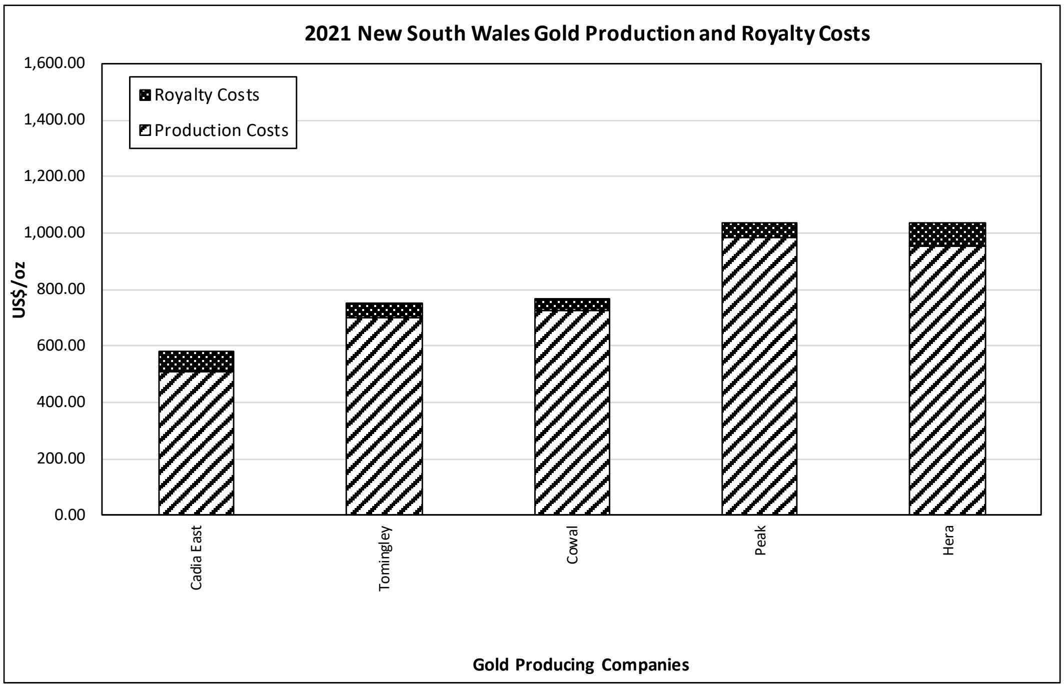

Figure 3-8. New South Wales primary gold mining companies mining costs with the royalty portion indicated (S&P Capital IQ, 2021).

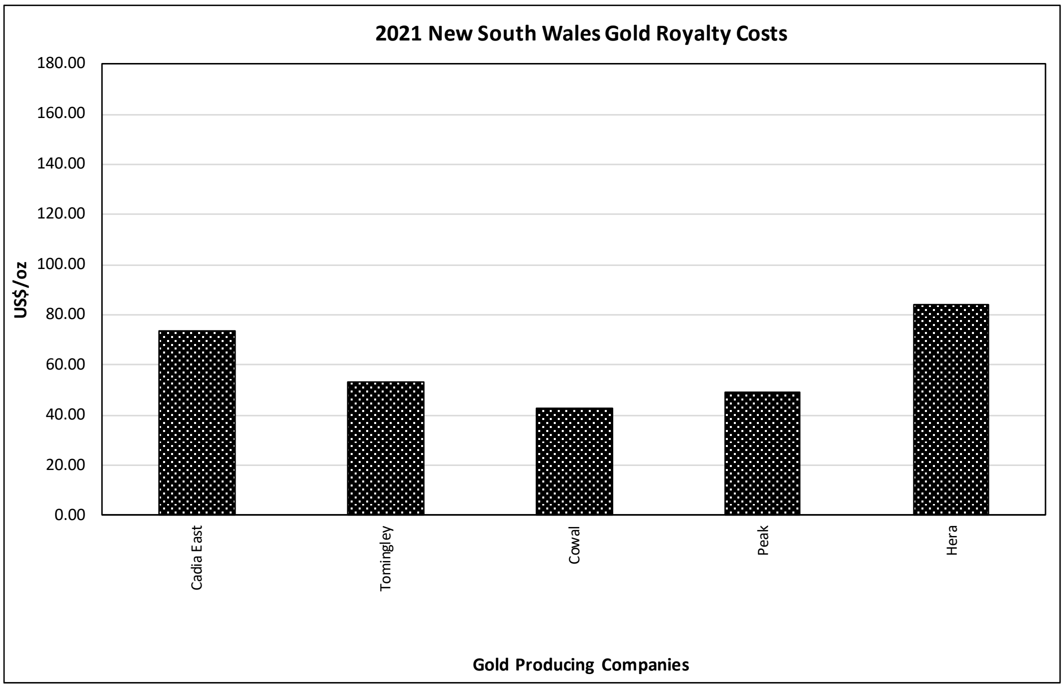

Figure 3-9. The royalty costs for the New South Wales gold mining companies (S&P Capital IQ, 2021).

The royalty costs range between US$43/oz and US$84/oz. These represent between 5% and 13% of the total mining costs.

Queensland’s rate is 2.7% of value or a variable royalty rate if the price exceeds a reference point, and Figure 3-10 shows the royalty as a portion of the total costs for the primary gold mining companies in Queensland, whilst Figure 3-11 shows the royalty costs.

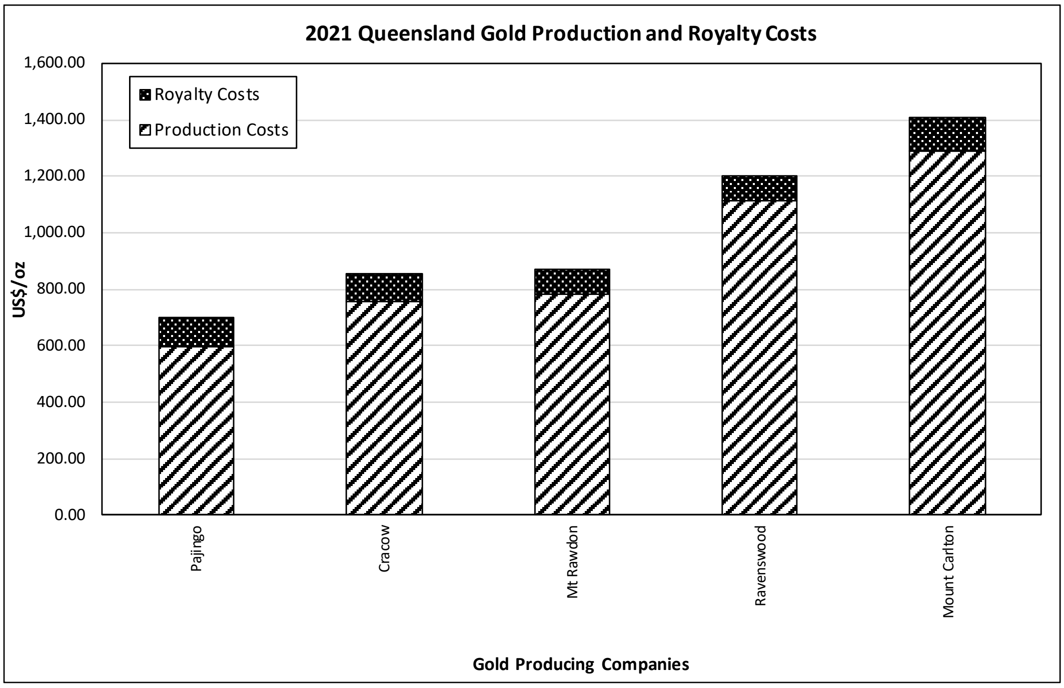

Figure 3-10. Queensland's primary gold mining companies mining costs with the royalty portion indicated (S&P Capital IQ, 2021).

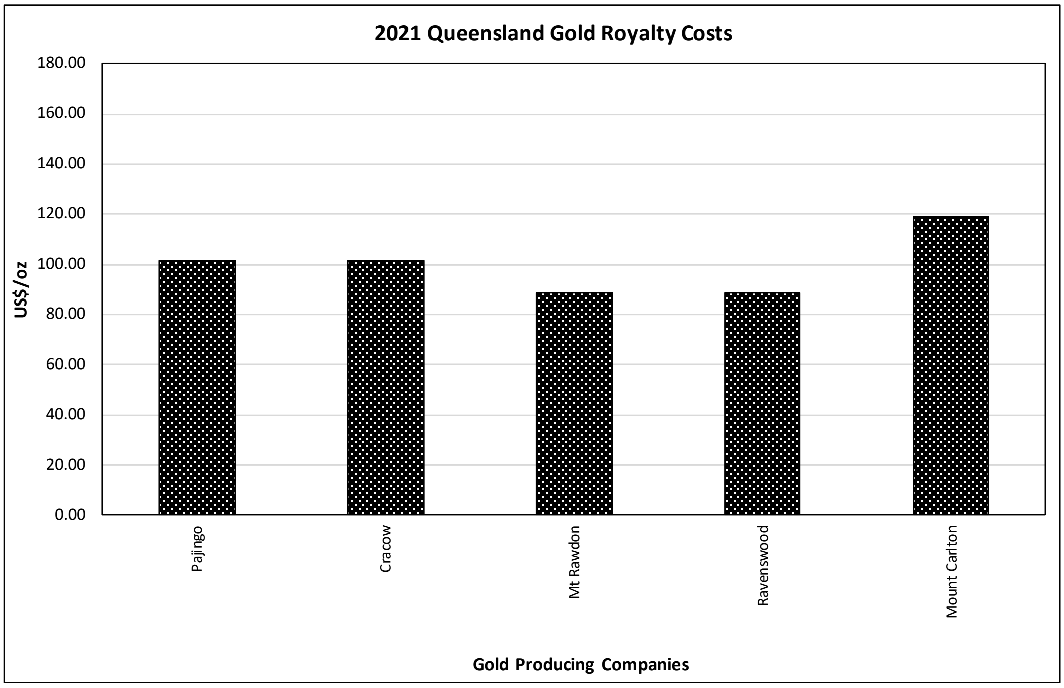

Figure 3-11. The royalty costs for the Queensland gold mining companies (S&P Capital IQ, 2021).

The Queensland royalty costs range between US$89/oz to US$119/oz. These costs are between 7% and 15% of the total mining costs.

Gold mining in Victoria is subject to a 2.75 % royalty. The royalty only applies to gold produced in a financial year over 2,500oz (Victoria State Government, 2021). Figures 3-12 and 3-13 show the royalty as a portion of the total and royalty costs (US$/oz) for the various Victorian primary gold mining companies.

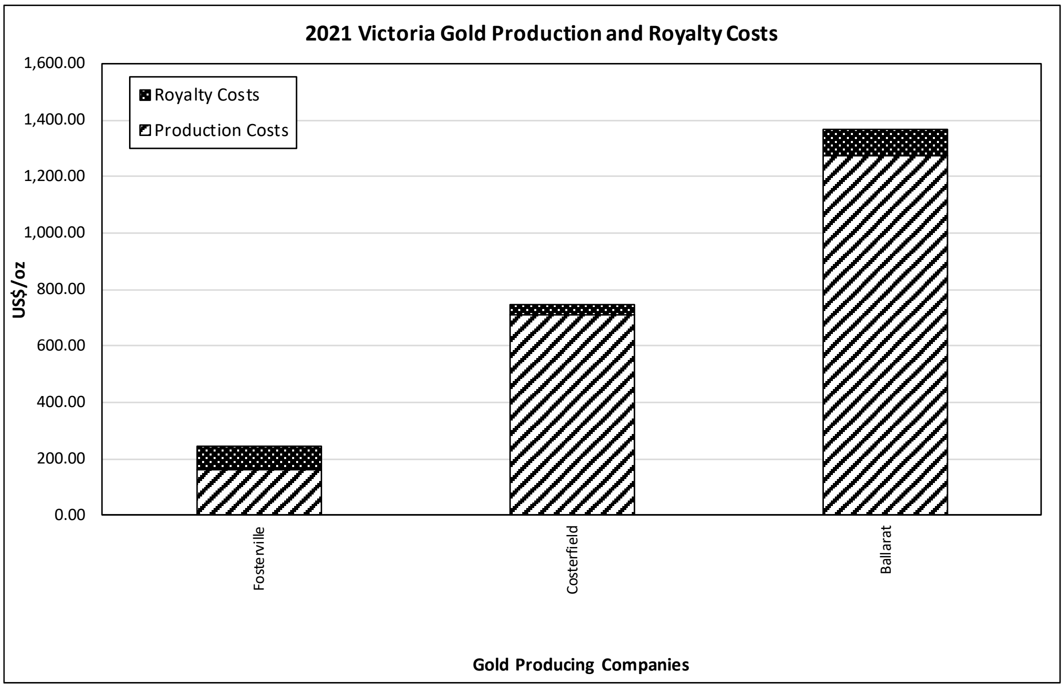

Figure 3-12. Victorian primary gold mining companies' costs with the royalty portion indicated (S&P Capital IQ, 2021).

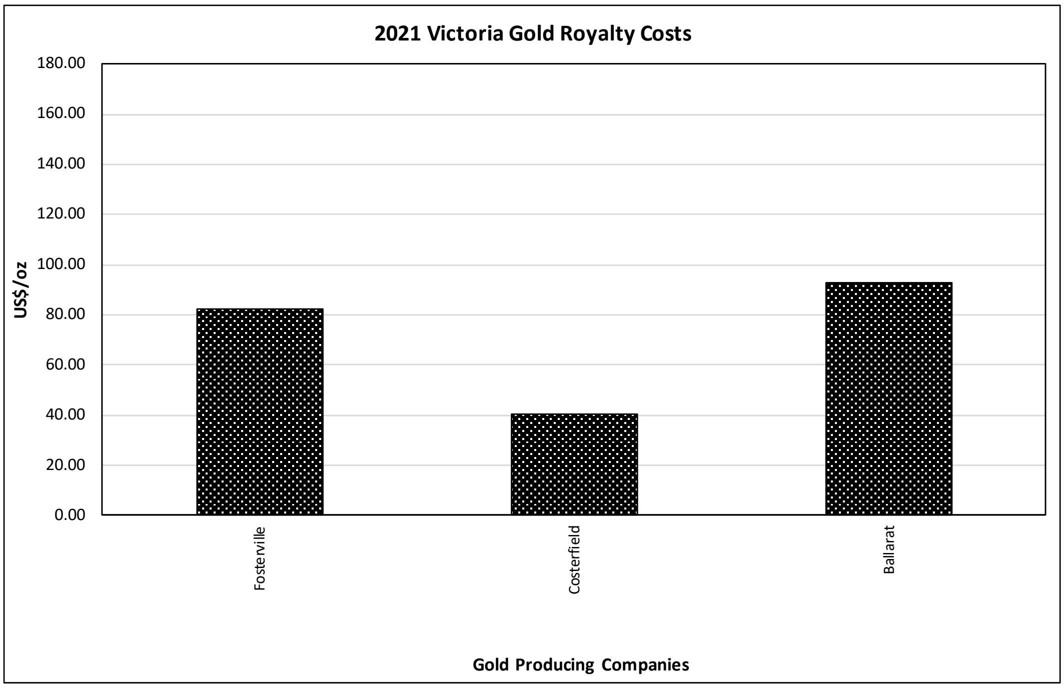

Figure 3-13. The royalty costs for the Victorian gold mining companies (S&P Capital IQ, 2021).

The Victorian gold mining royalties range from US$40/oz to US$93/oz. In the case of Fosterville, the royalty costs represent 34% of the total mining costs.

No relationship exists between profit and the royalty costs noted for the Australian gold-producing regions.

3.2.2 Burkina Faso

Burkina Faso charges 3% *ad valorem* on sales of precious metals. The royalty rates are indexed to gold prices and increase to 4% for gold prices between US$1,000/oz and US$1,300/oz, and 5% for prices above US$1,300/oz (Bouterige, 2020).

Figures 3-14 and 3-15 show the royalty as a portion of the total costs and the total royalty costs paid by the various Burkina Faso gold mining companies.

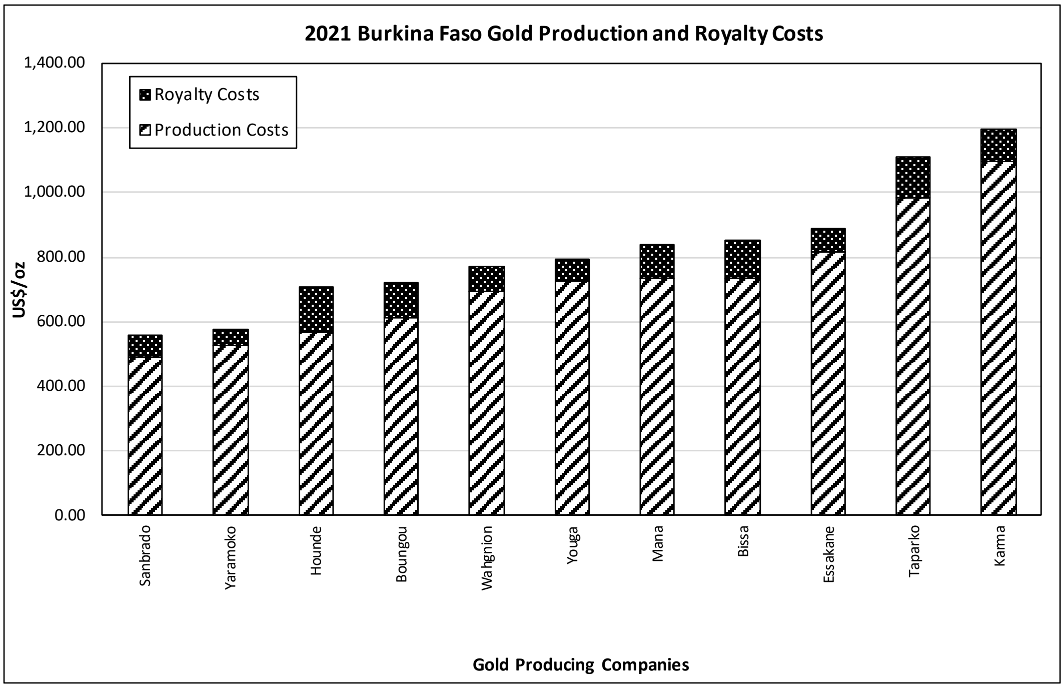

Figure 3-14. Burkina Faso's primary gold mining company costs with the royalty portion indicated (S&P Capital IQ, 2021).

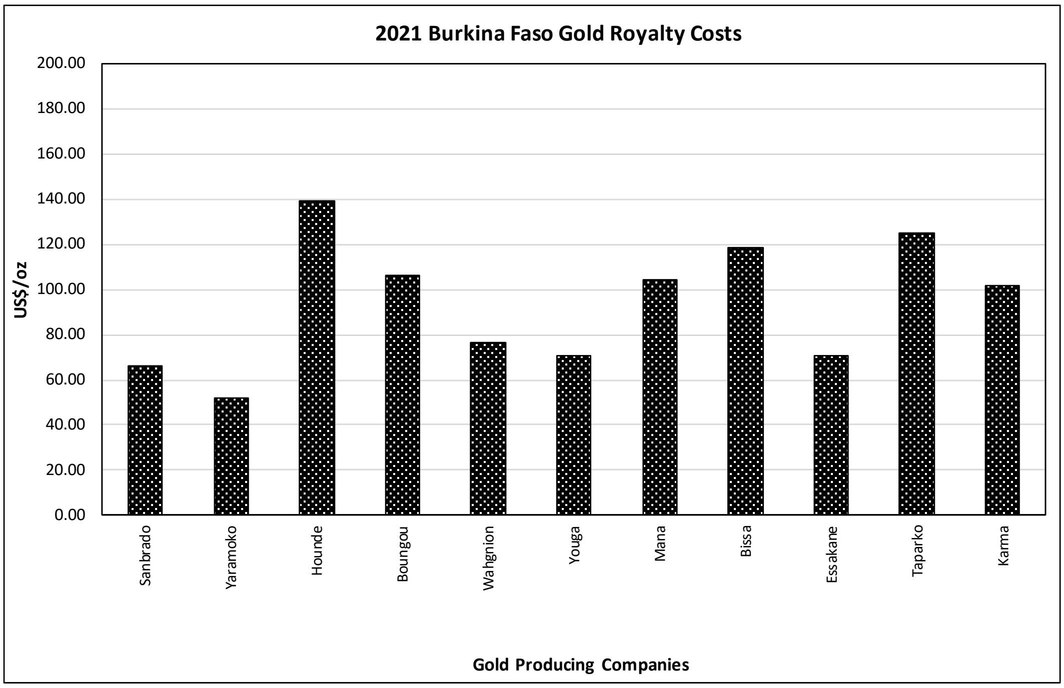

Figure 3-15. The royalty costs for the Burkina Faso primary gold-producing companies (S&P Capital IQ, 2021).

The royalty costs for Burkina Faso range from US$52/oz (Yaramoko) to US$139/oz (Hounde), with an average of US$94. The percentages of the royalty costs range between 9% and 20%. There is no general trend noted between profitability and royalty costs.

3.2.3 Canada

The mining royalty rates for Canada differ for the different regions and commodities. For gold, the following apply:

- British Columbia – More than 13% of net revenue less 2% of net proceeds, or 2% of net proceeds (Otto et al., 2006);
- Northwest Territories – 5-14% of output value (Otto et al., 2006);
- Ontario – 10% of defined profits (Otto et al., 2006);
- Québec – a fixed rate of 1% of the total output value at the mine shaft head below or equal to $80 million, calculated annually, but increasing to 4% for each dollar over the $80 million threshold. The output value at the mine shaft head is based on the gross value of

the annual output of the mine, less various mining expenses (Paradis & Gagnon, 2013);

- Newfoundland and Labrador – (called the Mining Tax). A 15% tax is imposed on the net income less allowable expenses (Government of Newfoundland and Labrador, 2022); and
- Saskatchewan – 5% of net profit (increases to 10% with lifetime production thresholds) (Otto et al., 2006).

Figures 3-16 and 3-17 show the royalty as a portion of the total costs and the royalty cost (US$/oz) paid by the various Canadian primary gold mining companies.

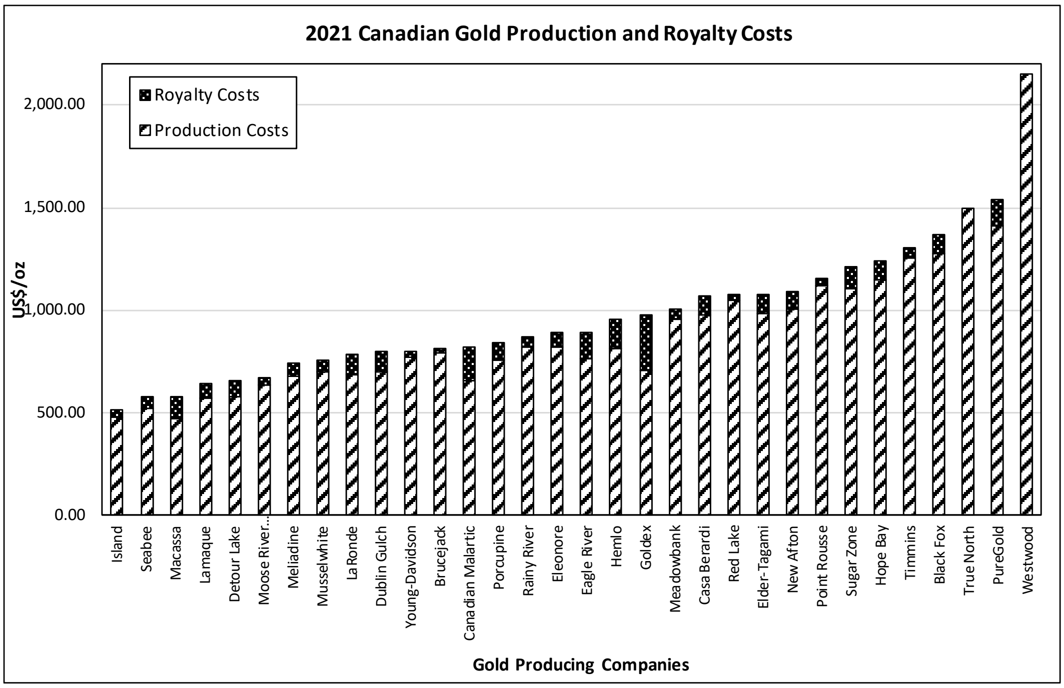

Figure 3-16. The costs of Canadian gold mining companies with the royalty portion indicated (S&P Capital IQ, 2021).

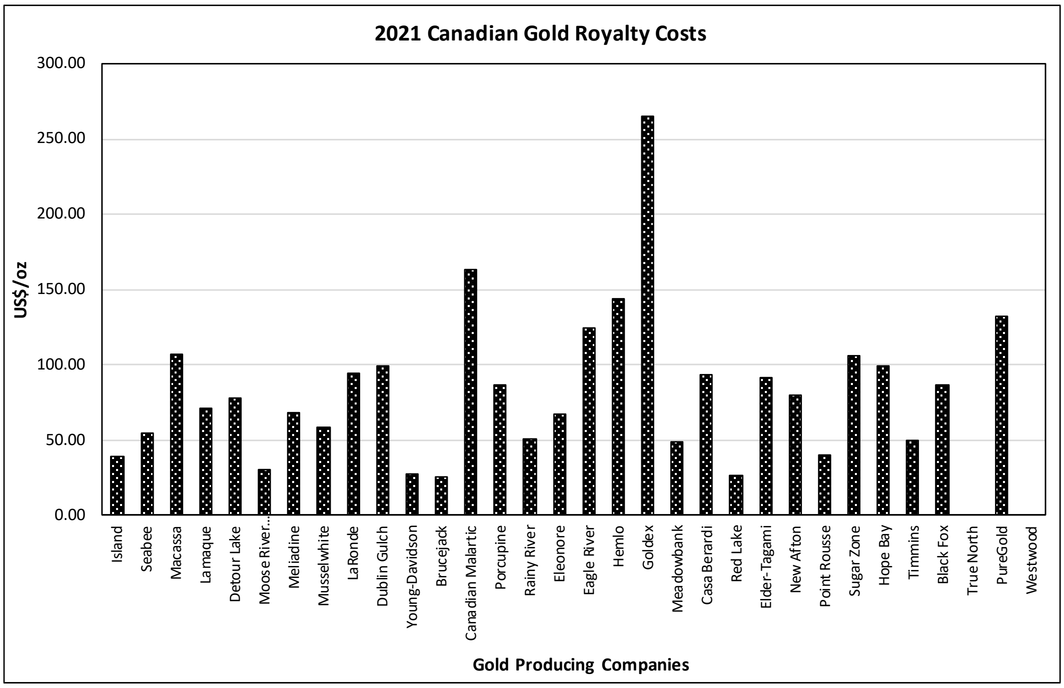

Figure 3-17. The royalty costs for the Canadian gold-producing companies (S&P Capital IQ, 2021).

The Canadian royalty costs range from US$0/oz (Westwood and True North) to US$265/oz (Goldex), with the average being US$86. The royalties represent between 0% and 27% of the total mining costs, with the average being 9%.

Figures 3-18 and 3-19 show the royalty as a portion of the total costs and the royalty cost (US$/oz) paid by the various British Columbian gold mining companies.

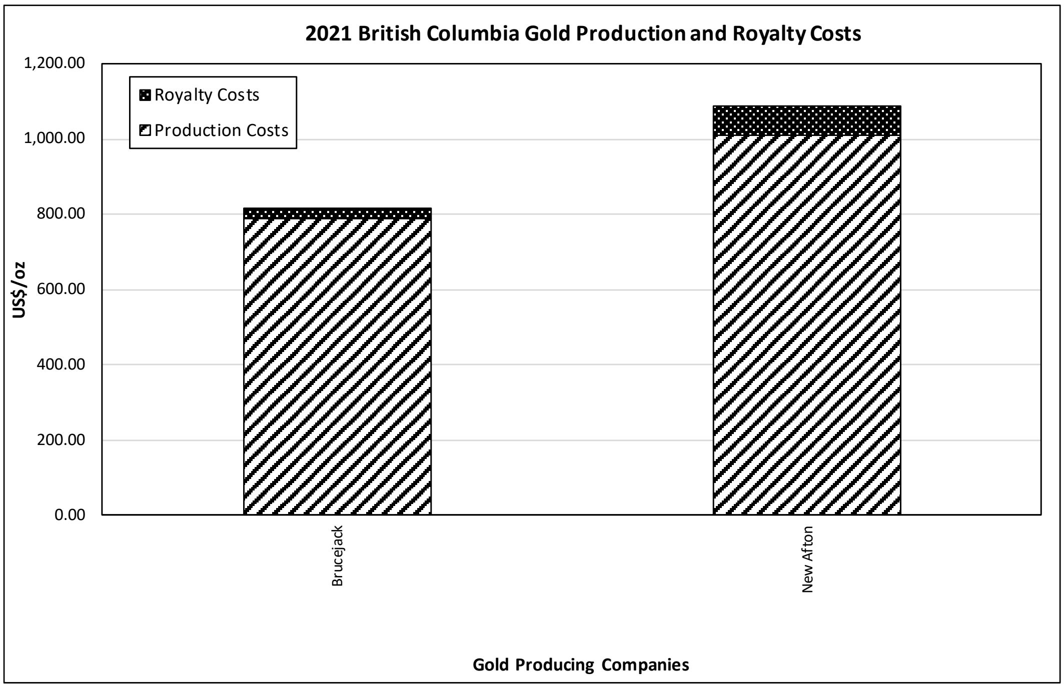

Figure 3-18. The costs of the British Columbian primary gold mining companies with the royalty portion are indicated (S&P Capital IQ, 2021).

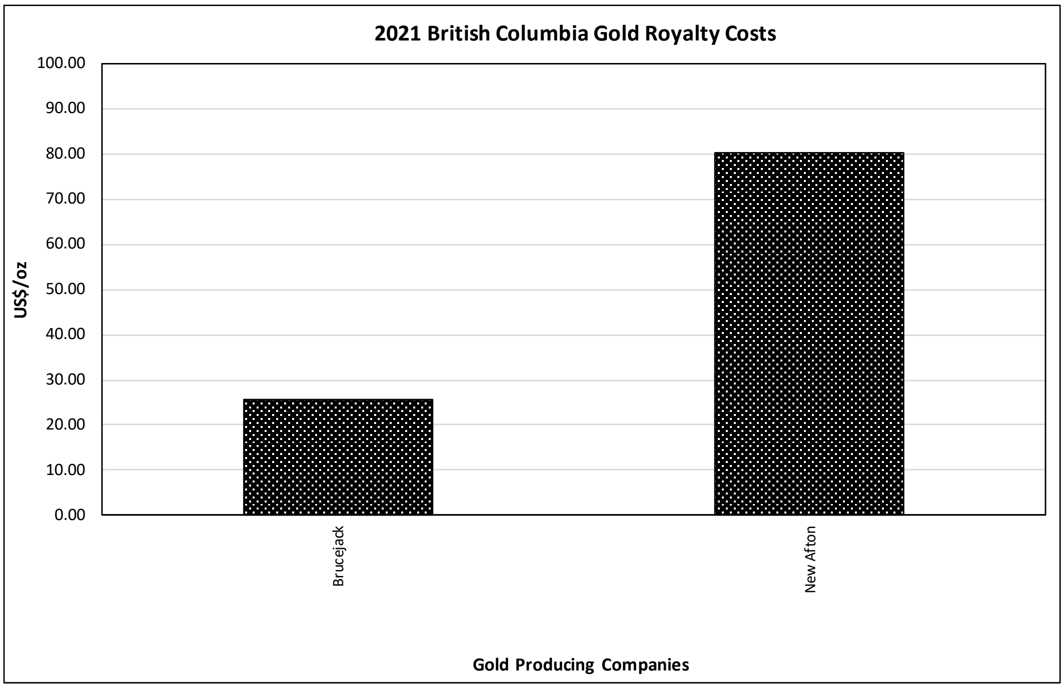

Figure 3-19. The royalty costs for primary British Columbian gold-producing companies (S&P Capital IQ, 2021).

Brucejack pays US$26/oz royalties, representing 3% of the total mining costs, while New Afton pays US$80/oz. This is 7% of the total cost. There is no relationship noted between profitability and the cost of the royalty.

Figures 3-20 and 3-21 show the royalty as a portion of the total costs and the royalty cost (US$/oz) paid by the various Ontario primary gold mining companies.

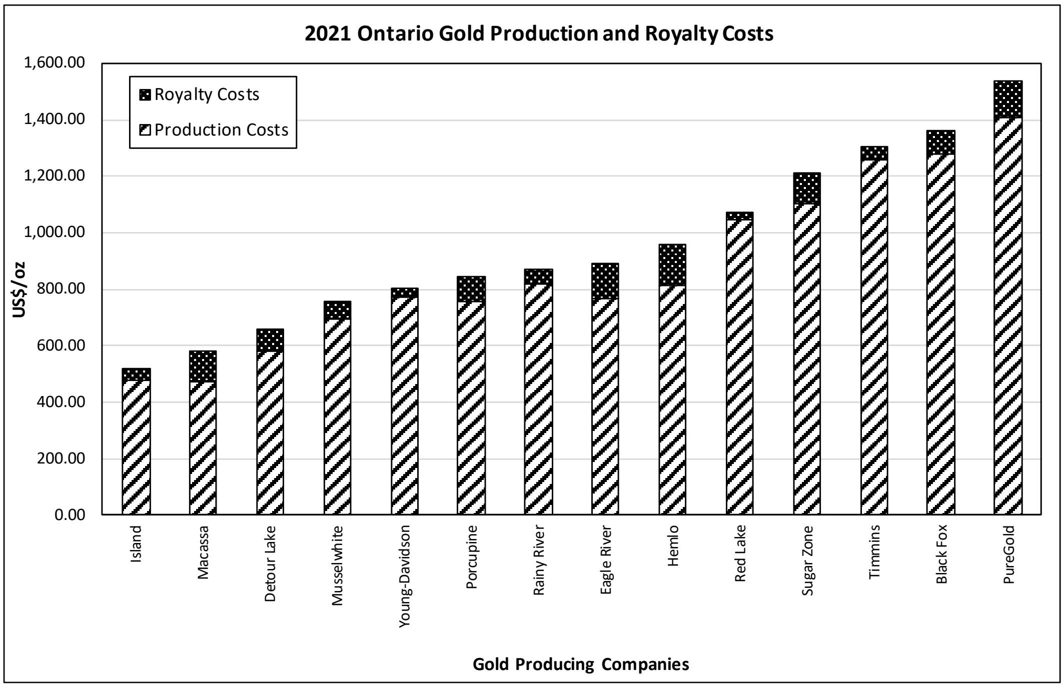

Figure 3-20. The costs of Ontario's primary gold mining companies with the royalty portion are indicated (S&P Capital IQ, 2021)

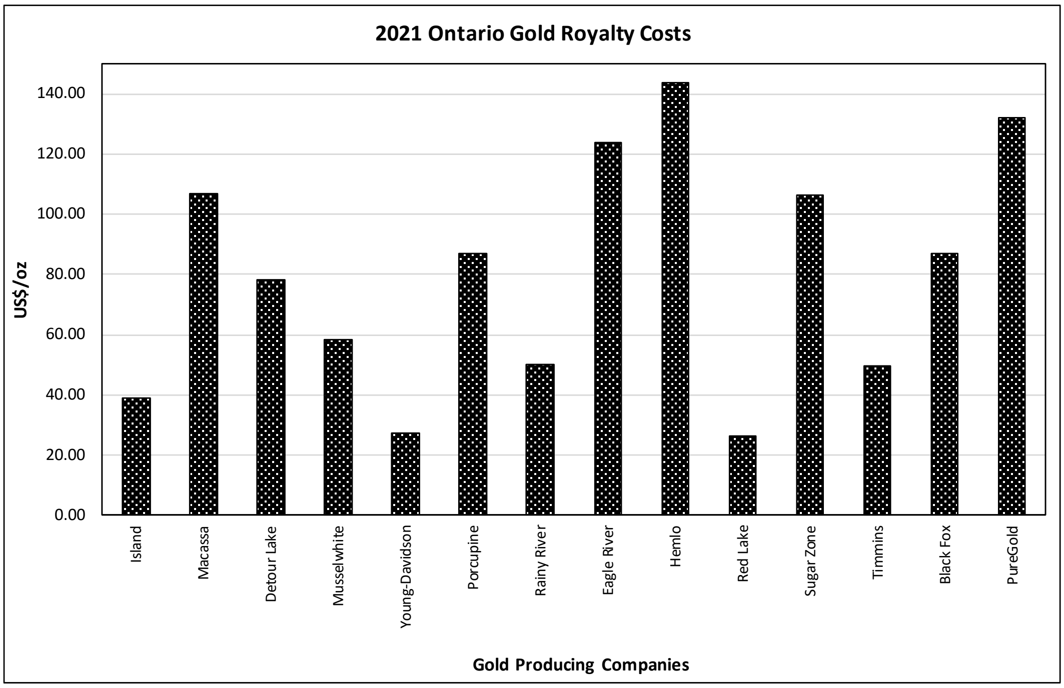

Figure 3-21. The royalty costs for the Ontario primary gold-producing companies (S&P Capital IQ, 2021).

The Ontario gold mining royalty costs represent 0% and 18% (Macassa) of the total mining costs for the primary gold mining companies. Hemlo has the highest royalty cost at US$144/oz.

Figures 3-22 and 3-23 show the royalty as a portion of the total costs and the royalty cost (US$/oz) paid by the various Québec gold mining companies.

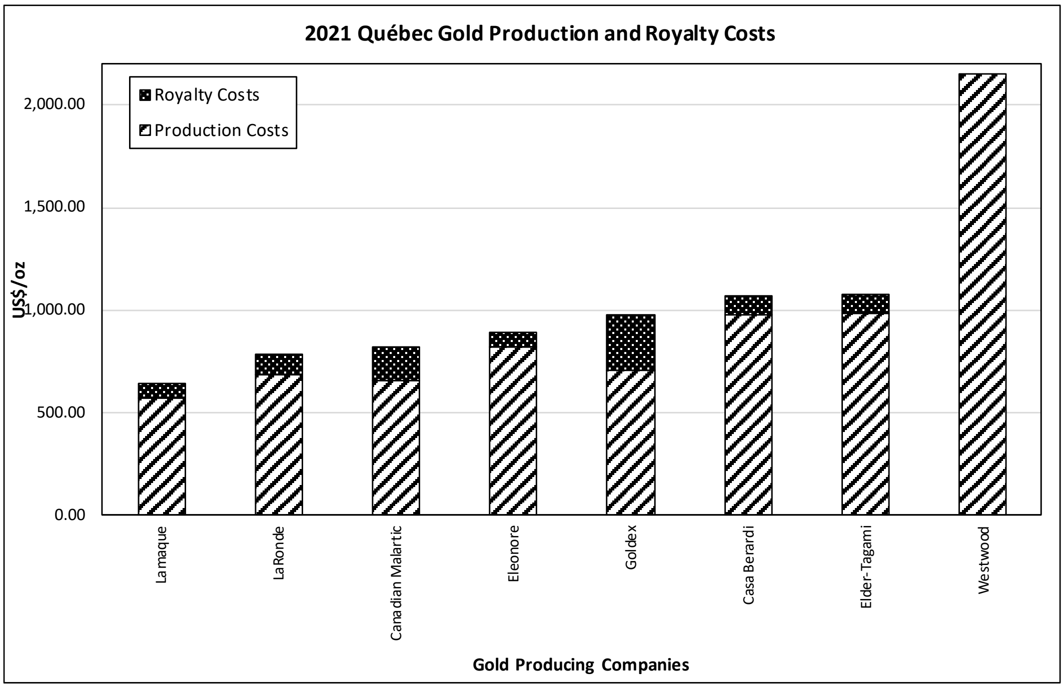

Figure 3-22. The costs of Québec's primary gold mining companies with the royalty portion are indicated (S&P Capital IQ, 2021)

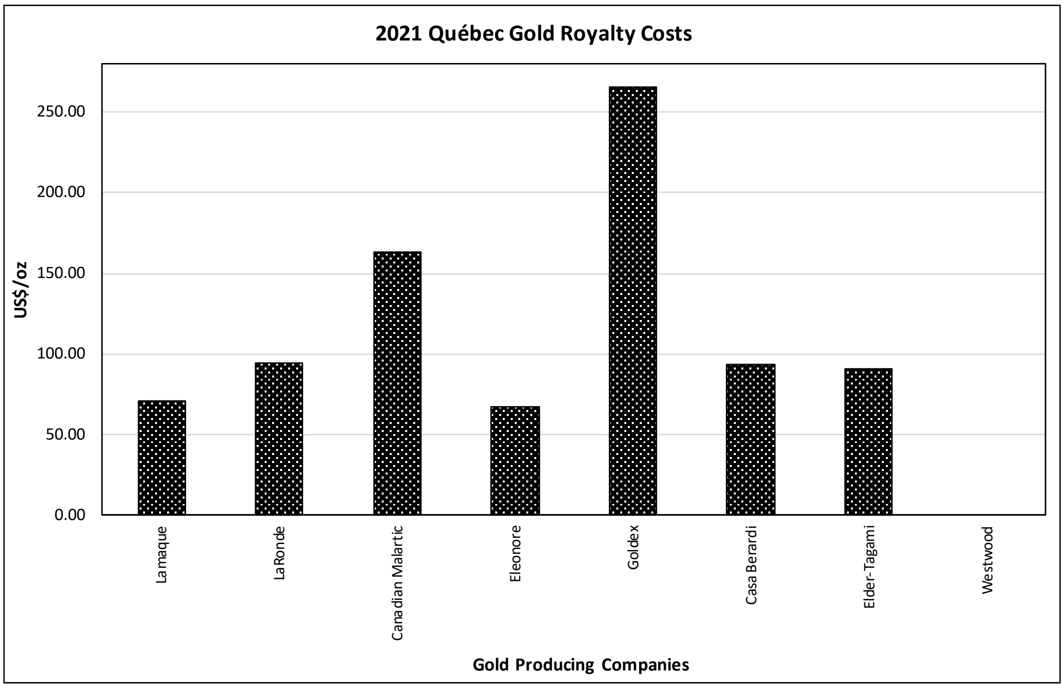

Figure 3-23. The royalty costs for Québec's primary gold-producing company (S&P Capital IQ, 2021).

Goldex pays royalty costs of US$265/oz, representing 27% of the total mining costs. The rest of the companies' royalty costs range from US$0/oz to US$163 (0% to 20% of the total production costs). There is no relationship between profitability and the cost of the royalty.

The other Canadian provinces are just represented by a single primary gold producer and have not been graphed.

3.2.4 China

China charges 4% *ad valorem* plus 0.4 to 30 yuan/tonne of ore for gold (Otto et al., 2006). Figures 3-24 and 3-25 show the royalty as a portion of the total costs and the royalty costs paid by the various Chinese gold mining companies.

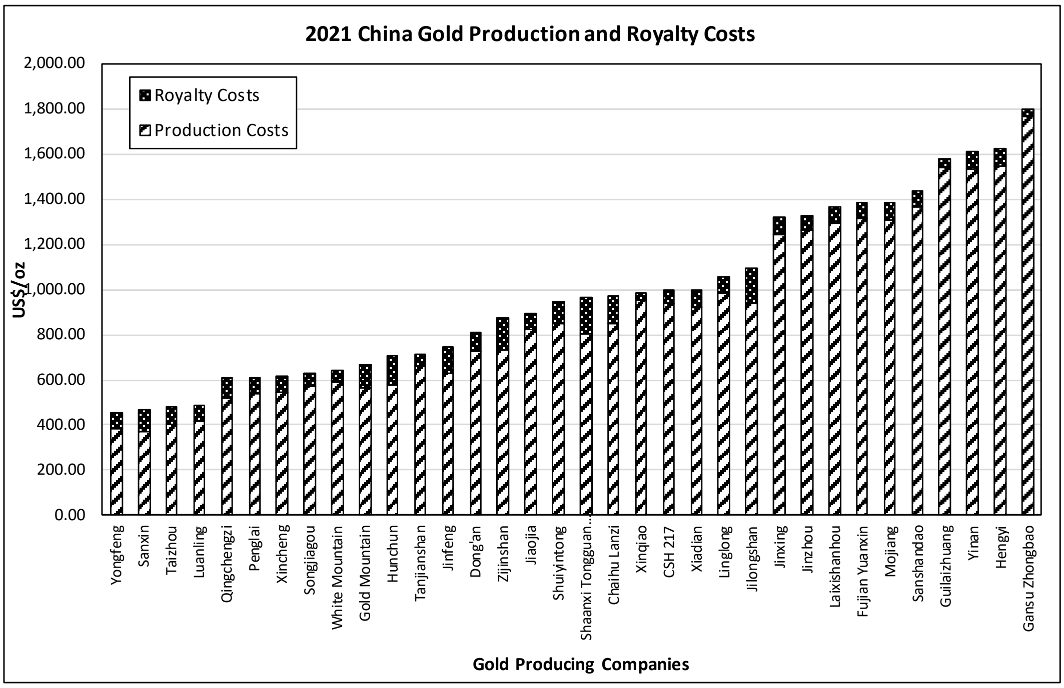

Figure 3-24. Chinese primary gold companies' mining costs with the royalty portion indicated (S&P Capital IQ, 2021).

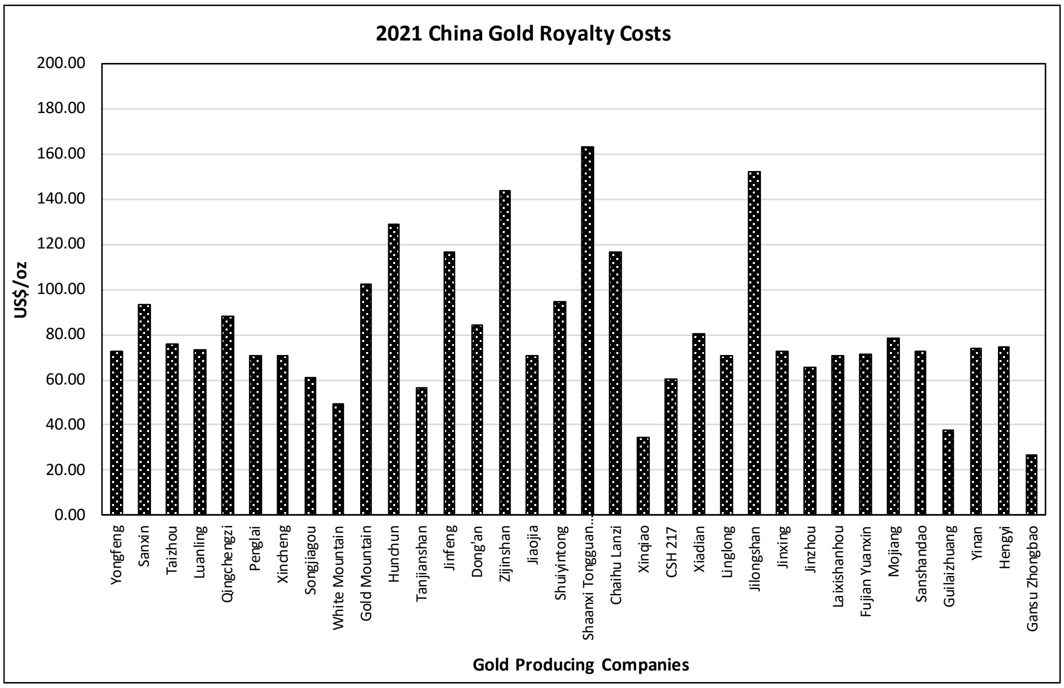

Figure 3-25. The royalty costs for the Chinese gold-producing companies (S&P Capital IQ, 2021).

The Chinese gold mining royalty costs range from US$27/oz (Gansu Zhongbao) to US$163/oz (Shaanxi Tongguan County Mine), with an average of US$83/oz. The royalties represent between 1% and 20% of the total mining costs. There is no relationship between profitability and royalty costs.

3.2.5 Ghana

Ghana previously had an *ad valorem* royalty rate that slides from 3% to 12% for gold, depending on costs (Otto et al., 2006). However, virtually all the companies were paying the minimum rate due to exploiting various loopholes to increase their costs (Gajigo, Mutambatsere & Ndiaye, 2012). In 2010, an *ad valorem* flat rate of 5% was introduced (Gajigo, Mutambatsere & Ndiaye, 2012). Figures 3-26 and 3-27 show the royalty as a portion of the total costs and the royalty cost paid by the various Ghanaian gold mining companies.

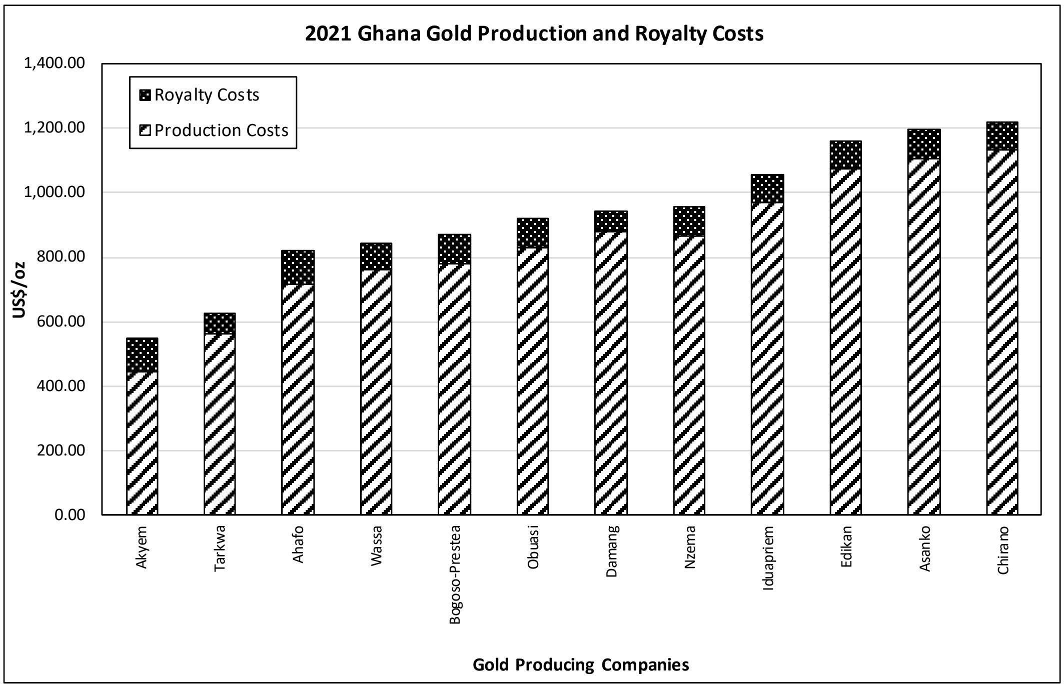

Figure 3-26. Ghanaian primary gold companies' mining costs with the royalty portion indicated (S&P Capital IQ, 2021).

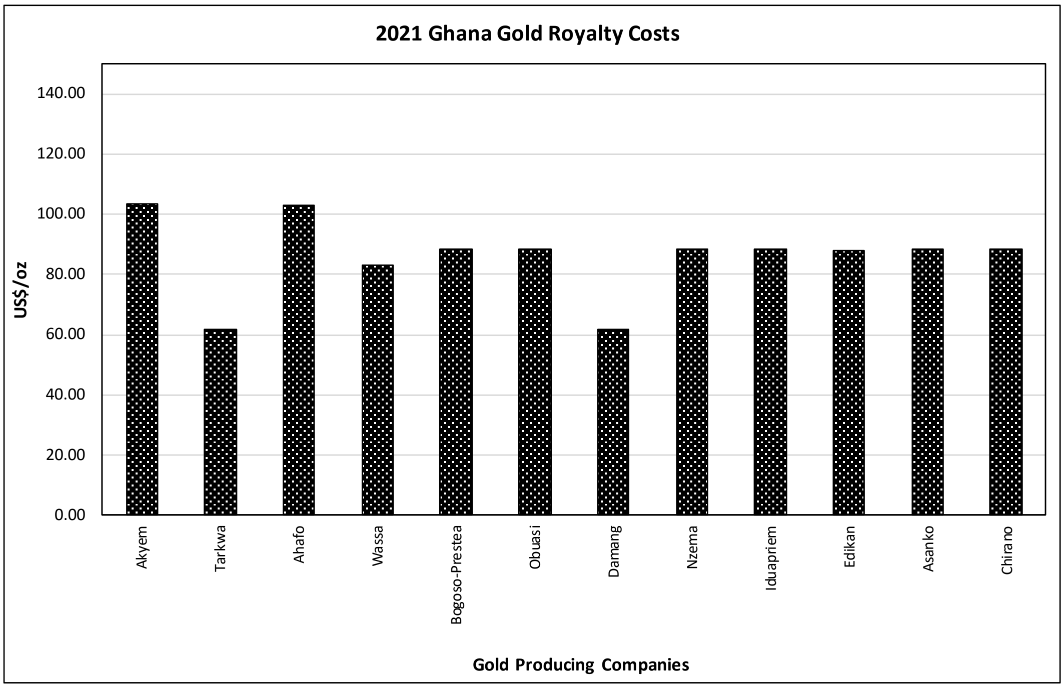

Figure 3-27. The royalty costs for the Ghanaian primary gold-producing companies (S&P Capital IQ, 2021).

It can be observed in the figure that Akyem has the lowest overall mining costs and pays US$104/oz for the royalties (representing 19% of the total mining costs). Tarkwa and Damang have the lowest royalty costs at US$62/oz. The average royalty cost is US$86/oz. The royalty costs range between 7% and 19% of the total mining costs.

3.2.6 Mexico

Prior to 2014, Mexico did not charge mining royalties. However, this changed, and it is currently 7.5% of the income from the sale of minerals extracted from a mining concession minus the authorised deductions. In addition, gold, silver and platinum mining pay an additional 0.5% of the income for selling such minerals to finance the environmental erosion impact of such mining activities (Cuellar & Paris, 2014). Figures 3-28 and 3-29 show the royalty as a portion of the total costs and the royalty cost paid by the various Mexican gold mining companies.

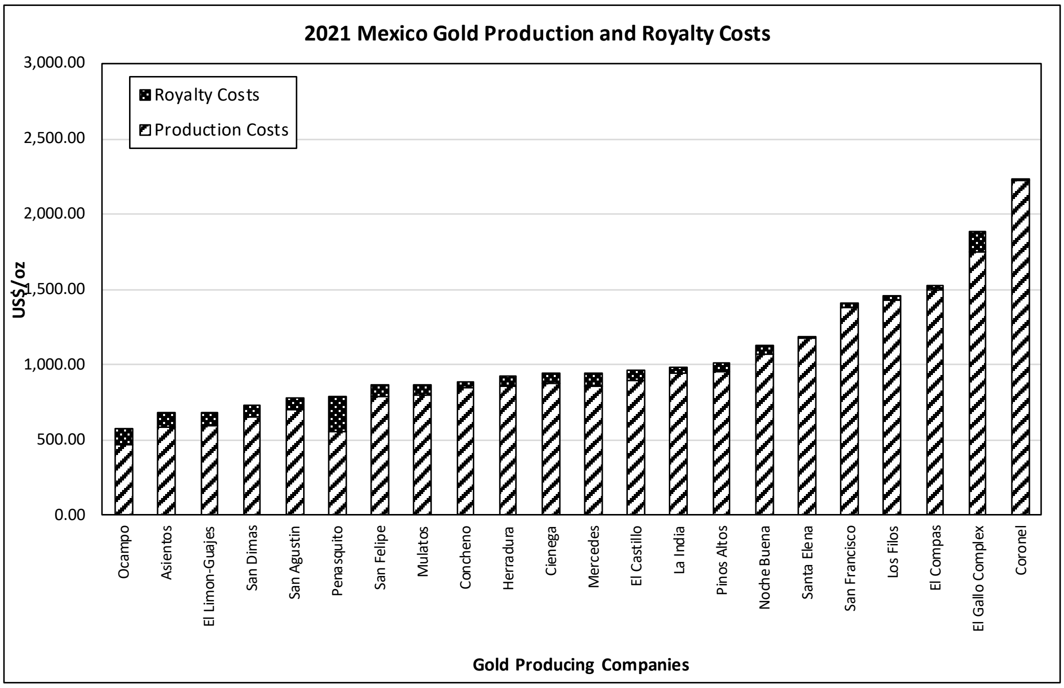

Figure 3-28. Mexican mining companies' costs with the royalty portion are indicated (S&P Capital IQ, 2021).

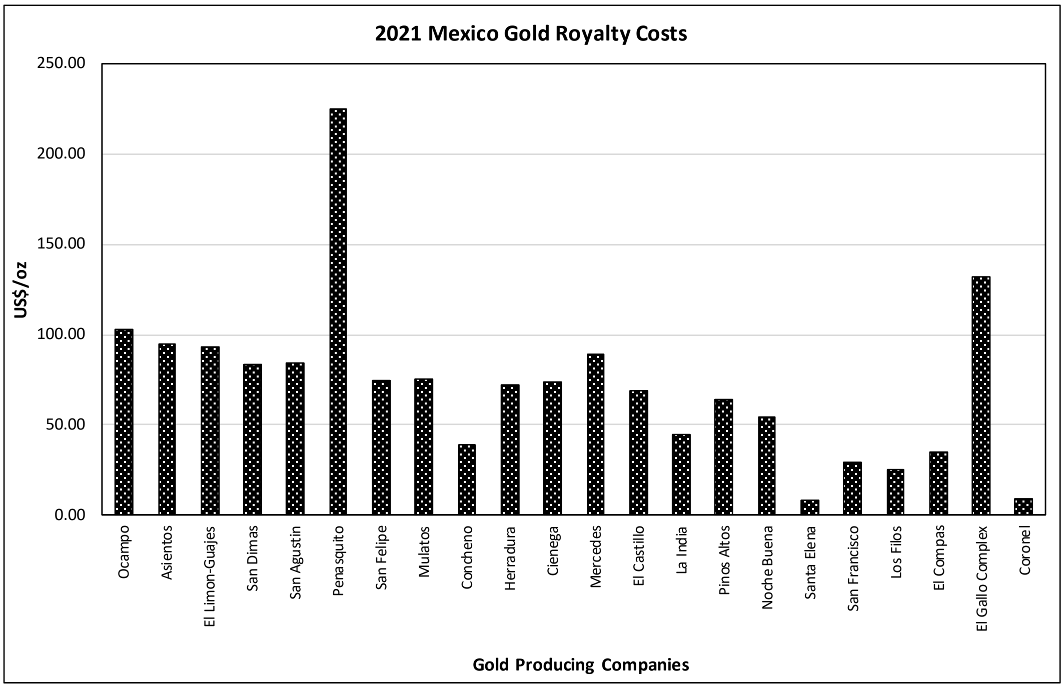

Figure 3-29. The royalty costs for the Mexican primary gold-producing companies (S&P Capital IQ, 2021).

It can be observed in Figure 3-29 that there appears to be no correlation between the overall mining costs and the percentage attributable to the royalty charges. However, this is predominantly due to the outliers observed with Penasquito and El Gallo Complex. If these very high royalty costs are removed, there is a clear relationship between profitability and royalty costs. The lowest-cost producers (Ocampo and Asientos) have royalty costs of US$103/oz and US$95/oz, respectively. The highest-cost producer (Coronel) pays just US$8/oz in royalty costs. The average royalty cost for Mexico is US$106/oz representing 12% of the total mining costs.

3.2.7 Russia

The mining royalty rate for gold is 6% *ad valorem* in Russia (PricewaterhouseCoopers, 2012). Figures 3-30 and 3-31 show the royalty as a portion of the total costs and the royalty costs paid by the various Russian primary gold mining companies.

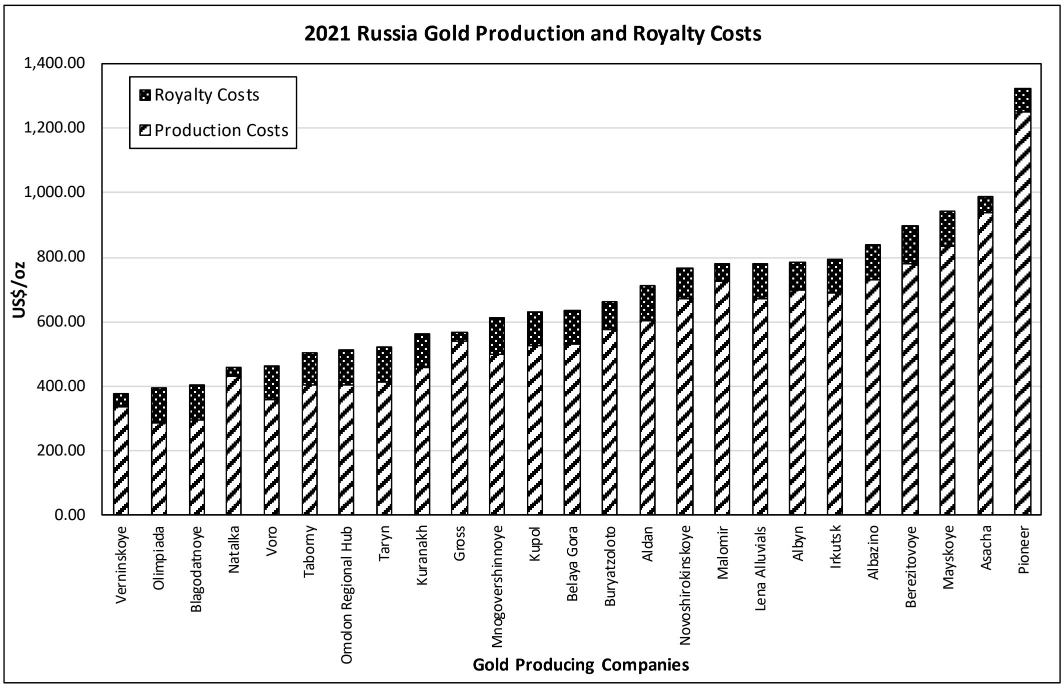

Figure 3-30. Russian primary gold companies' mining costs with the royalty portion indicated (S&P Capital IQ, 2021).

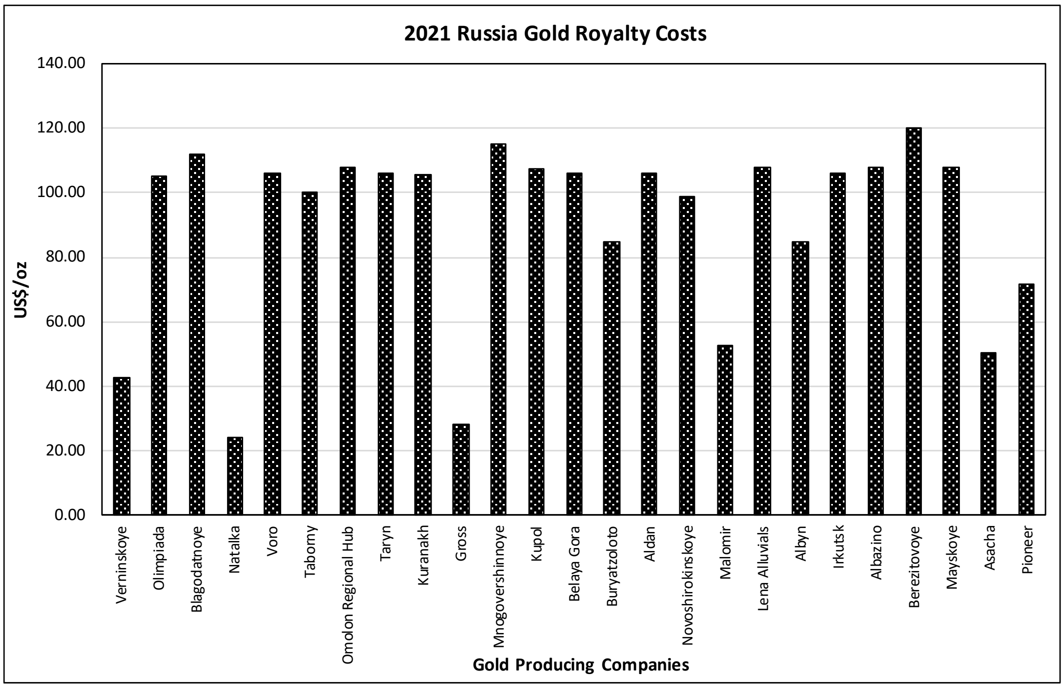

Figure 3-31. The royalty costs for the Russian primary gold-producing companies (S&P Capital IQ, 2021).

The average royalty cost in Russia is US$88/oz (representing 15% of the total mining cost). Mnogovershinnoyepays the highest royalties (US$115/oz). This represents 19% of the total mining costs. Natalka has the lowest royalty costs (US$24/oz), which is 5% of the total mining cost. The other companies' royalty costs are between 5% and 28% of the total mining costs. Because the royalty is a flat rate based on revenue, no relationship is observed between the total royalty costs and the overall mining costs (profitability).

3.2.8 South Africa

The details of the South African royalties and the applicable formulas and rates are covered in Chapters 1 and 2. Figures 3-32 and 3-33 show the royalty as a portion of the total costs and the royalty cost paid by the various South African primary gold mining companies.

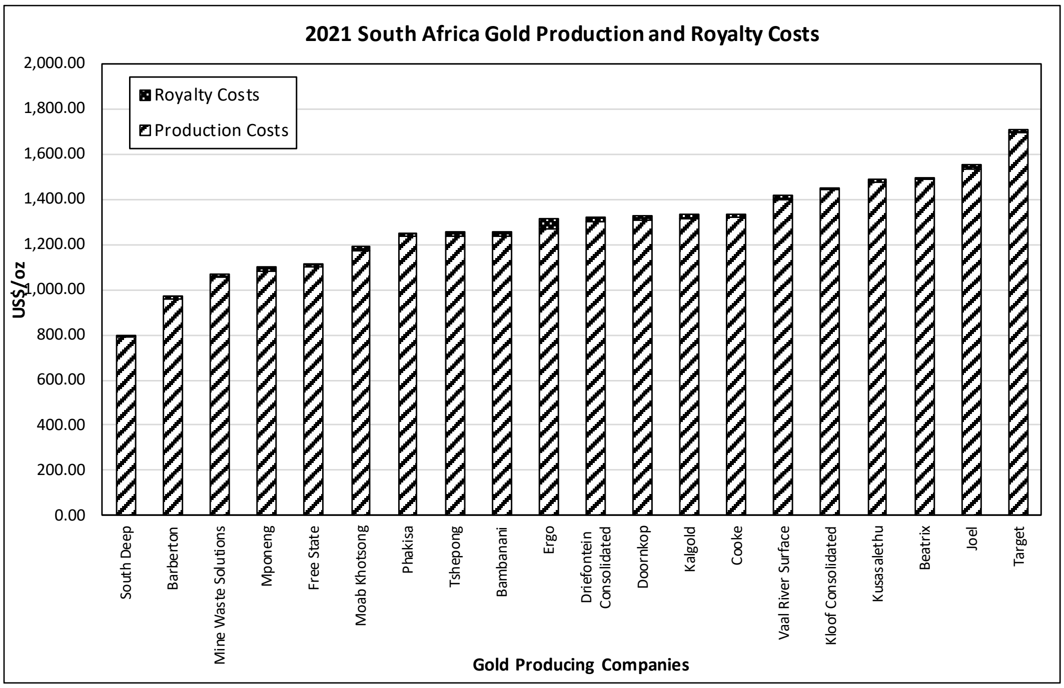

Figure 3-32. South African primary gold mining companies' mining costs with the royalty portion indicated (S&P Capital IQ, 2021).

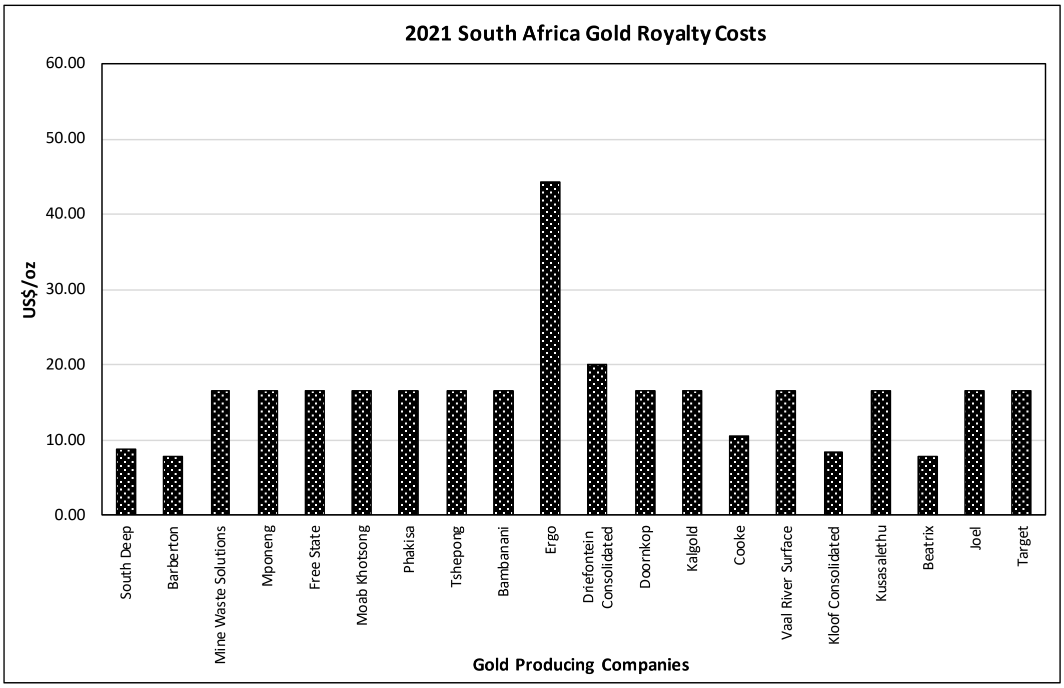

Figure 3-33. The royalty costs for the South African primary gold-producing companies (S&P Capital IQ, 2021).

The South African royalty costs range from US$8/oz (for Barberton and Beatrix) to US$44/oz (Ergo). Overall, South Africa has the lowest royalty costs at an average of US$15/oz of any significant gold-producing country. The percentage that the royalty costs contribute to the overall costs ranges from 1 to 3%, which is also the lowest of any of the top ten gold-producing countries. However, this is a function of the highest mining costs as much as the actual royalty costs. The royalty rate is flexed on profitability, and due to the high mining costs, the resultant royalty costs are relatively low.

This reflects the high costs of deep-level underground mining at many South African gold mines.

3.2.9 United States

The mining royalties in the United States are very complex and dependent on which state the mine is located and the type of land (Federal, State, Native American, or private). It also varies for the commodity being mined (Otto et al., 2006). The approaches applied for determining royalty rates are generally *ad valorem* or unit-based, although profit-based systems are also used. Some approaches follow sliding scales based on net proceeds (Otto et al., 2006).

Figures 3-34 and 3-35 show the royalty as a portion of the total costs and royalty costs paid by the various United States primary gold mining companies.

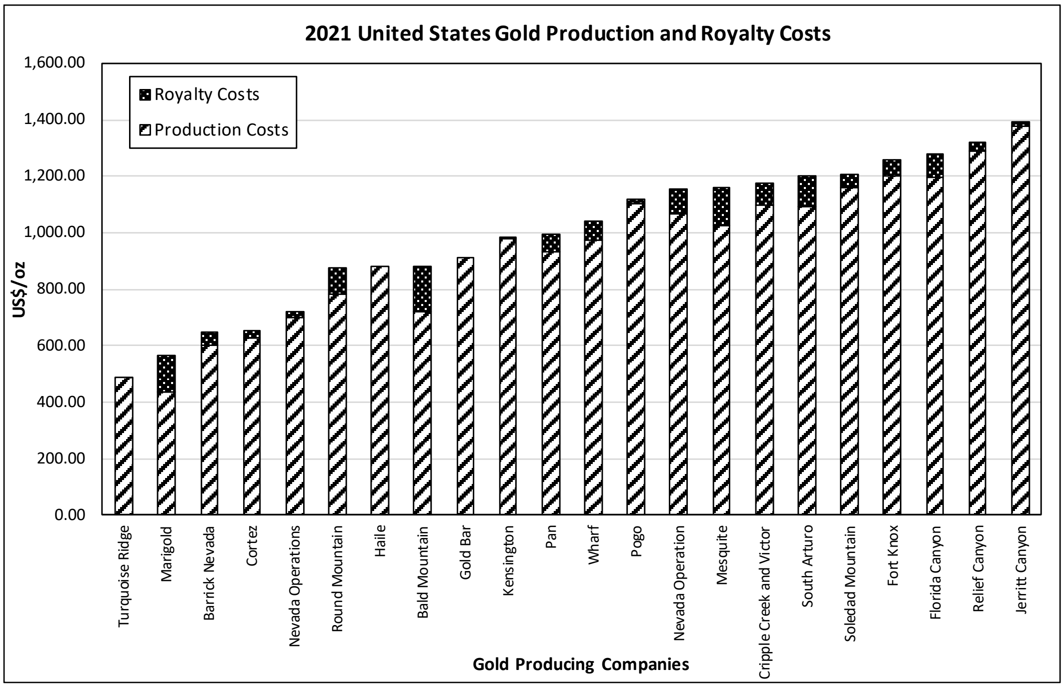

Figure 3-34. The United States mining companies' costs with the royalty portion are indicated (S&P Capital IQ, 2021).

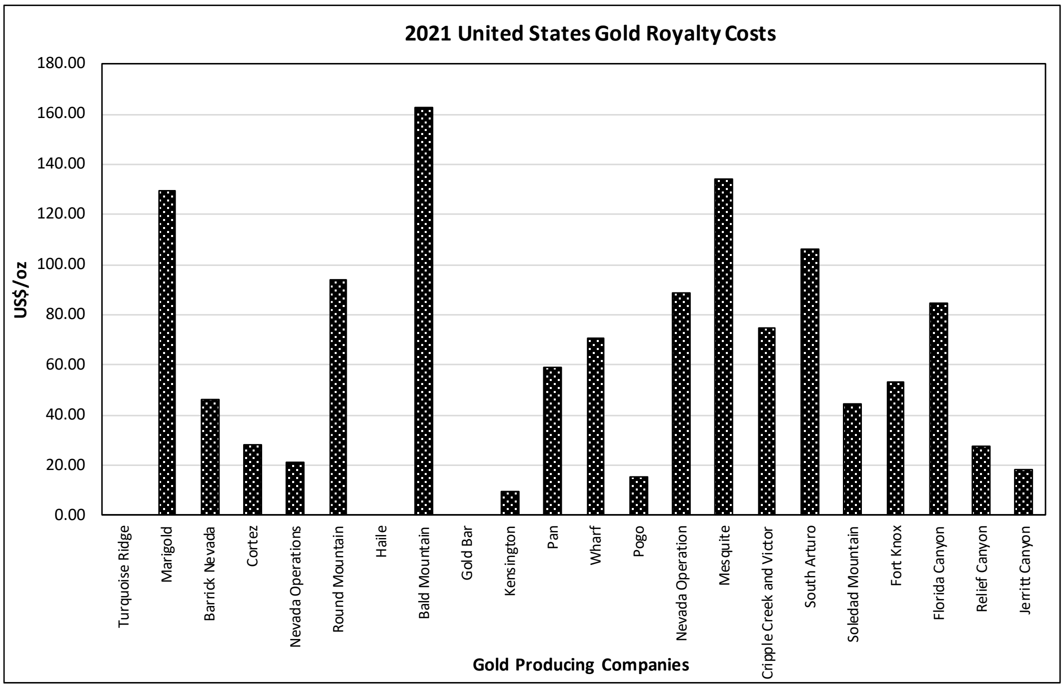

Figure 3-35. The royalty costs for the United States' primary gold-producing companies (S&P Capital IQ, 2021).

The average royalty rate for the United States is US$44/oz. This ranges from US$0/oz (Turquoise Ridge, Haile and Gold Bar) to US$163/oz (Bald Mountain). This represents 5% of the overall mining cost.

The Nevada State rate for gold mining royalties is 5% and is applied to the net proceeds above US$4 million per year 5% (Otto et al., 2006).

Figures 3-36 and 3-37 show the royalty as a portion of the total costs and royalty costs paid by the various Nevada primary gold mining companies.

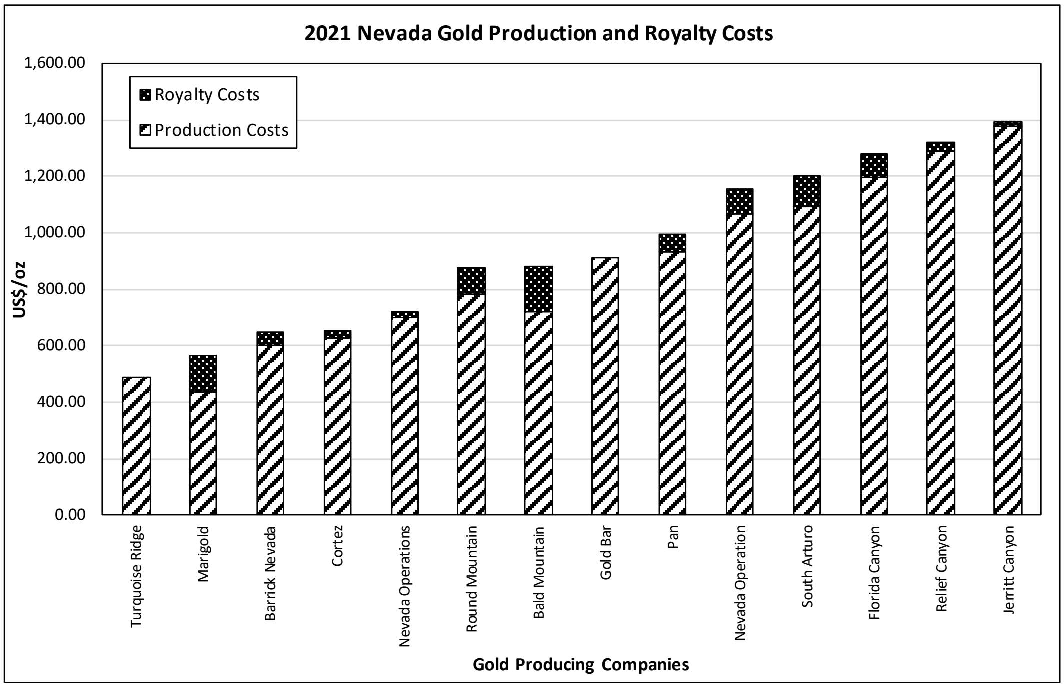

Figure 3-36. The Nevada mining companies' costs with the royalty portion are indicated (S&P Capital IQ, 2021).

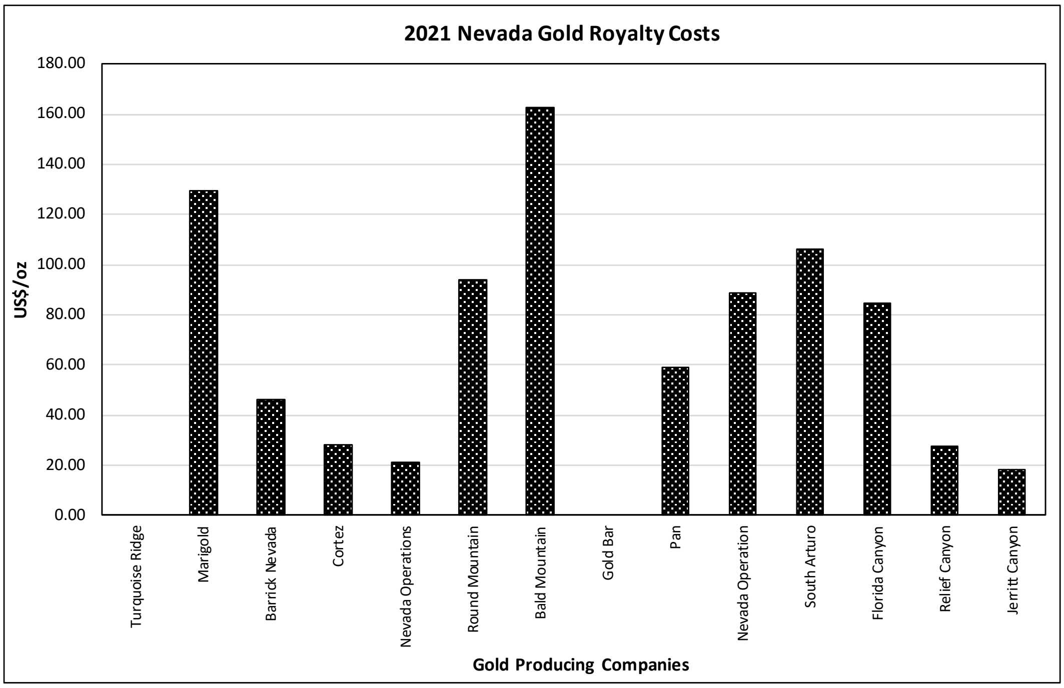

Figure 3-37. The royalty costs for the Nevada primary gold-producing companies (S&P Capital IQ, 2021).

No trend is noted between the overall mining and royalty costs for the Nevada primary gold producers. The royalty costs range between US$0/oz to US$163/oz (representing 18% of the total mining costs).

Figures 3-38 and 3-39 show the royalty as a portion of the total costs and the royalty costs paid by the various Alaskan primary gold mining companies.

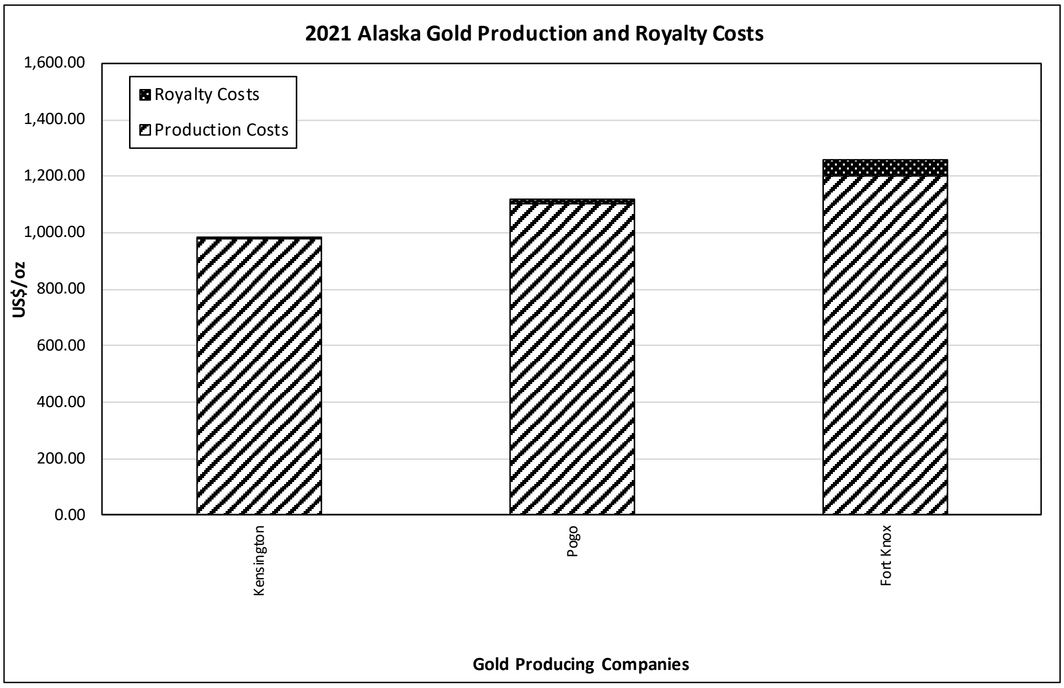

Figure 3-38. The Alaskan mining companies' mining costs with the royalty portion are indicated (S&P Capital IQ, 2021).

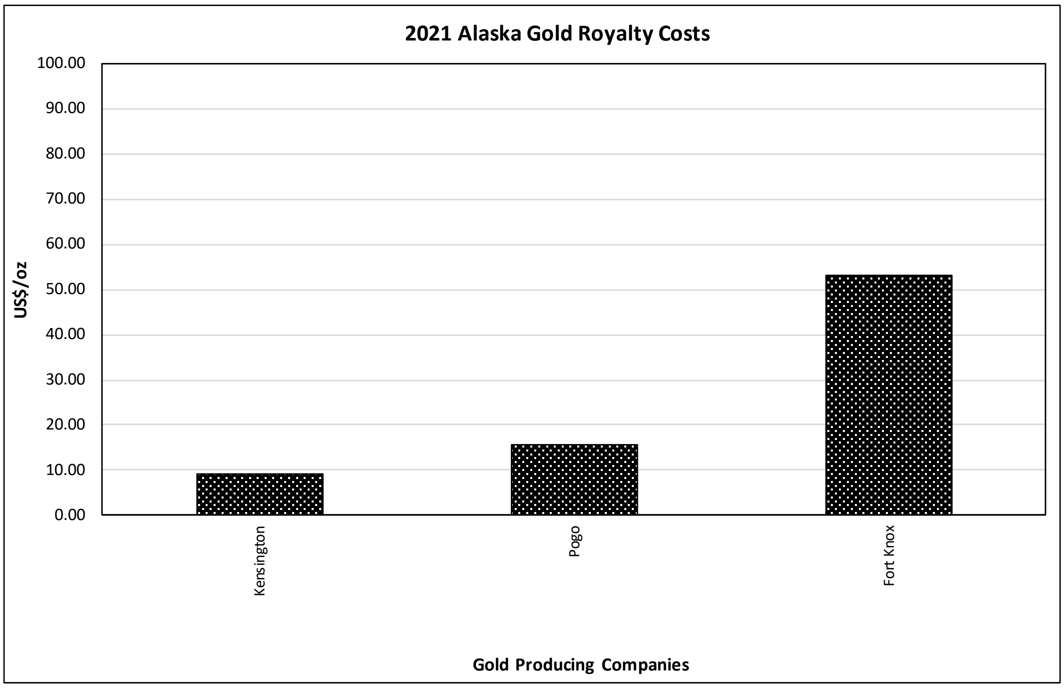

Figure 3-39. The royalty costs for the Alaskan primary gold-producing companies (S&P Capital IQ, 2021).

In Alaska, mining royalties are 3% of the net income calculated through the Mining License Tax. The companies can deduct the rent they pay to the state for their claim/lease that produced the mineral (Feige, 2022). For the primary gold producers reviewed, the royalty costs range from US$9/oz to US$53/oz (representing 4% of the total mining costs).

Figures 3-40 and 3-41 show the royalty as a portion of the total costs and the royalty costs paid by the various Californian primary gold mining companies.

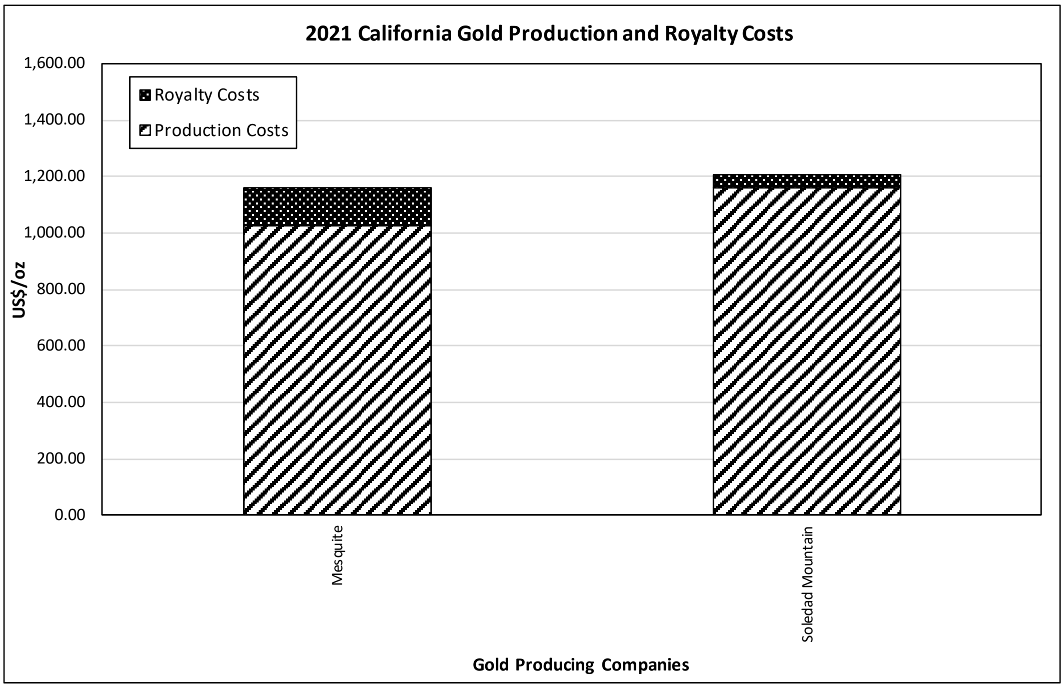

Figure 3-40. The Californian mining companies' costs with the royalty portion are indicated (S&P Capital IQ, 2021).

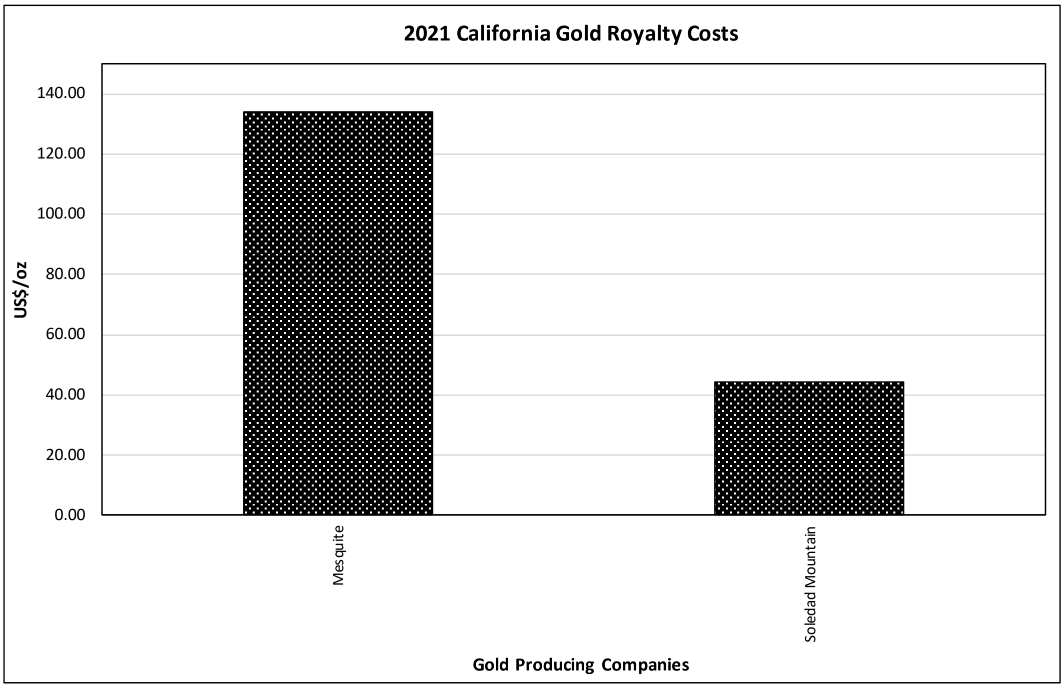

Figure 3-41. The royalty costs for the primary Californian gold-producing companies (S&P Capital IQ, 2021).

3.2.10 Uzbekistan

Uzbekistan's mining royalty is referred to as the subsurface use tax. It is imposed on the sale price of extracted natural resources and varies between 2.6 and 30% of the sales revenue depending on the commodity (for example, gold 25%, silver 25%, copper 15%, zinc 10%, uranium 10% and coal 4%) (Lexology, 2019). There is also a waste charge that varies between 0.78 and 9%. In addition, there is an excess profit tax of 50% (Azizov & Partners, 2018).

In 2021, the Navoi Mining & Metallurgical Combinat State Co. paid US$128/oz in royalty charges, representing 29% of the total mining costs.

3.3 Chapter Summary

It was noted that there is a vast diversity in the cost of mining royalties paid in the various top ten gold-producing countries in 2019. This ranges from US$15/oz (South Africa) to US$128/oz (Uzbekistan). As percentages of total mining costs, this range is from 1.2% to 29%. Outside the top ten gold-producing countries, Kyrgyzstan (US$255/oz), Turkey (US$128/oz), Tanzania (US$163/oz) and Armenia (US$157/oz) are found to have royalty costs for 2021 that are higher than Uzbekistan.

For the individual gold-producing mines, the highest royalty was paid by Goldex in Canada (US$265/oz). This was followed by Beta Hunt (Australia), Shaanxi Tongguan County Mine (China), Canadian Malartic (Canada) and Bald Mountain (United States), which all had royalty costs in 2021 of above US$160/oz.

This review of the royalty costs found in the top ten gold mining companies globally has shown significant differences in how different countries determine the royalty costs. The predominant way is some form of *ad valorem* royalties based on the value of the mineral sold. Some countries allow some costs to be deducted when determining the amount to be paid. The South Africa hybrid approach with a profit-based sliding scale applied to the total value of the mineral sold appears to be unique. This affects how the royalty costs should be considered for the cut-off grade determination. The accepted approach for *ad valorem* royalties is to consider them a mining cost and include the cost in the cut-off grade calculation.

South Africa has the lowest overall royalty costs of the top ten countries. Compared to the overall mining cost, the percentage these costs represent is also significantly lower than any of the other countries (1.2% compared to an average of 9.2%). However, this favourable situation is partly due to the high overall mining costs found in South Africa (US$1257/oz) compared to the other top ten gold mining countries (average of US$803/oz). These high-cost mining companies are more likely to run marginal mines, so the royalty charges are more likely to sterilise portions of the ore bodies.

Chapter 4 will consider how cut-off grades are determined and how the mineral resource royalties are considered in the different optimisation approaches.

4 REVIEW OF CUT-OFF GRADE OPTIMISATION APPROACHES

4.1 Introduction

This chapter will review the evolution of cut-off grade optimisation and give a broad overview of some of the approaches used in Southern African mining operations.

4.2 The Evolution of Cut-off Grade Optimisation

Cloete applied the pay limit concept around 1910 in the South African context of gold mining on the Witwatersrand (Innes, 1923). The gold ore was mined without producing a profit or loss as per legal requirements at the time.

In the 1932 book on Witwatersrand Mining Practice, it is stated that *"If the value of the block is estimated to be sufficient to cover the cost of mining and extraction of gold and give a profit, it is classified as payable, and the total ore in the fully developed payable blocks constitutes the Ore Reserve".* Furthermore, it is stated that *"the quality and value of the ore in the reserve may be looked upon as the main asset of a mining company"* (Watermeyer & Hoffenberg, 1932: 791).

Henning (1963) and Lane (1964) considered how the cut-off grades could optimise the NPV over the life of the asset rather than being a point-in-time calculation. In his book *"The Economic Definition of Ore"*, Lane (2016) describes the economic principles of how cut-off grades are derived and how cut-off grades can be optimised at various stages of a mine's life. The algorithm considers three main constraints: mining, concentrating, and refining. Economic factors (selling price and unit costs) and technical factors (the grade distribution and the various mine capacities) are included in the algorithm to maximise the profit or NPV. The NPV is usually considered the dominant economic criterion because it considers the time value of money (TVM) (Lane, 2016).

Storrar (1981) describes the *"pay limit of an ore is the minimum value at which it can be mined and treated without profit or loss"* (Storrar, 1981: 145). While the cut-off grade and pay limit descriptions sound the same, they will be considered two separate processes for this study. A cut-off grade is applied on a mining block-by-mining block basis, whilst the pay limit is applied mine-wide, which was a legal requirement that the mining grade may not exceed the average grade of the payable ore reserve. The practical implication of this study is the effect of managing the ore body to prolong the life of the mine and protect employment. The average mining grade (AMG) from a mine managing the ore body using the cut-off grade approach is that this grade is effectively the average grade from all the blocks above the cut-off grade. The AMG is calculated as the pay limit with an accepted (as approved by the Inspector of Mining Leases at the time) profit margin when managing the ore body using the pay limit. The blocks mined are then selected to achieve this pay limit grade. The legal requirement to mine to the average grade was abandoned in 1991 after the Minerals Act of 1990 became effective. For this study, the cut-off grade approach has been used to optimise the financial model, although some mines use the pay limit approach or a combination of cut-off grades and pay limits. South African gold producers have tended to mine to the economic cut-off grade. In practical terms, the cut-off grade falls when prices rise, and vice versa (Crowson, 1998).

The advent of computers and the use of geostatistics combined with financial modelling allowed more sophisticated models to be employed, cutting the time and person-hours associated with time-consuming manual calculations. The resource could now be divided into smaller blocks representing the smallest mining unit (SMU). Halls et al. approached determining the optimal ore reserves and plant size by conducting incremental financial analysis in 1969 (Halls, Bellum & Lewis, 1969).

4.3 Overview of Cut-Off Grade Approaches and Optimisation

Hotelling developed an extraction strategy for exhaustible resources in 1931, where the price would grow at a rate equal to the interest rate. This, he indicated, would ensure that a competitive resource owner would deplete the resource at a socially acceptable rate (Devarajan & Fisher, 1981; Macfarlane, 2006). He identified that profits are related to the current production and remaining in the resource. Hotelling also identified that resource prices are affected by monopolies, extraction costs increase with cumulative production and demand decreases due to durable commodities like gold and diamonds (Devarajan & Fisher, 1981).

Githiria and Musingwini (2018) compared the various cut-off grade models in mine planning for improved value creation based on NPV. They identified that the different approaches could be divided into the following broad categories:

- Break-even cut-off grade approach;
- Heuristic cut-off grade approach; and
- Lane's optimum cut-off grade approach.

Furthermore, Camus considered the optimal path of extraction in 2002, resulting in a variable cut-off grade strategy over the life of the operation (Macfarlane, 2006).

For some commodities, the cut-off grade strategy is not purely financial but rather geological. This is termed a geological cut-off grade (Pasieka & Sotirow, 1985).

4.3.1 Break-even cut-off grade approach

The break-even cut-off grade approach is the most basic cut-off grade optimisation and is essentially very simple. It determines the grade required for an ore unit to return a profit. It assumes a known volume (usually limited to shaft capacity, mill capacity, or other physical constraints) (Githiria & Musingwini, 2018).

Equation 5 (School of Mining Engineering, 2021a) can explain the break-even grade formula.

At break-even grade:

$$TR = TFC + TVC$$

Where: TR is the total revenue, TFC is the total fixed costs, and TVC is the total variable costs.

But:

$$TR = UR * X$$

And:

$$TVC = UVC * X$$

Where: UR is the unit revenue, UVC is the unit variable cost, and X is the units of production.

Therefore:

$$UR * X = TFC + UVC * X$$

Dividing both sides by X:

$$UR = (TFC \div X) + UVC$$

But:

$$UR = units/t * r * p$$

Where: $units/t$ is the break-even grade in units per tonne; r is the mine recovery factor in %; p is the metal price in US$ per unit.

Therefore at break-even grade $(units/t)$:

$$\text{units}/t = ((TFC \div X) + UVC) \div (r * p) \quad \text{Equation 5.}$$

These are all estimates and subject to mine and market variation through the period, thus adding to the investors' financial risk if these change significantly.

The mining industry widely accepts this method to ensure the operation remains profitable. However, there are limitations, including that TVM is ignored, resulting in sub-optimum NPV. Since the break-even model only considers price and costs, the variability in grade estimations, geology conditions and operational capacities influencing revenue are overlooked (Pettingell, 2017).

4.3.2 Heuristic cut-off grade approach

Heuristic algorithms sacrifice optimality, accuracy, precision or completeness for speed (Kenny, Nathal & Saldana, 2014). These are often used to solve decision problems quickly and where absolute accuracy is not critical. There are several approaches, including swarm intelligence and genetic algorithms. Some have been applied to optimise the cut-off grade in mining applications (Githiria & Musingwini, 2019).

Due to heuristic approximation approaches focusing on maximising the NPV, cut-off grade optimisation generally results in cut-off grades higher than those obtained through the break-even approach in the project's early years. This increase in the cut-off grade is due to recovering the initial capital investment. Later in the project life, cut-off grades reduce to the same or even lower than those obtained through the break-even approach, and the heuristic approaches maximise extraction (Rendu, 2014; Githiria & Musingwini, 2018). Dagdelen (1992) noted that heuristic approaches do not consider capacity constraints and opportunity costs (Dagdelen, 1992).

4.3.3 Lane's optimum cut-off grade approach

Lane's approach to cut-off grade optimisation (1964) identified an optimum extraction strategy for depleting a finite mineral resource, defined as the path to the maximum NPV. He realised that each successive increment of depletion should maximise the remaining resources' NPV (Macfarlane, 2006). He also considered the constraints imposed by various interdependent components of the mining operation and how they affect the optimum cut-off grade. The mine, mill and refinery (market) have their capacities, and the optimum cut-off grade balances these to maximise the NPV of future cash flows. His model is a three-dimensional process that considers the mining limiting cut-off grade, the concentrator limiting cut-off grade and the refinery (market) limiting cut-off grade (Lane, 1964, 2016). This has led to a ‘balancing cut-off grade’ in which the mining, milling and marketing systems balance fully utilising these capacities (Macfarlane, 2006).

This approach is not widely applied in South Africa because it is considered too complex. However, the fundamentals are important, and it has been built into some existing mine planning and optimisation software, including Maptek Evolution®, OIpitPit®, and Geovia Wittle 4X® (Githiria & Musingwini, 2018).

Githiria and Musingwini (2018) found that in their comparison of the various cut-off grade models in mine planning for improved value creation based on NPV, the classical approach generated a single cut-off grade. The modern techniques altered the cut-off grade through the various phases of the mine's life (dynamic cut-off grades). They noted that Lane's approach has been used successfully but is limited to a single commodity. They also determined that all factors (economic, technical, legal, environmental, social and political) should be considered when calculating the cut-off grades (Githiria & Musingwini, 2018).

4.3.4 The Camus approach

Camus identified economic value add (EVA) as an appropriate metric for mineral resource management (Macfarlane, 2006). This approach for exploiting an exhaustive resource splits it into increments. Each increment is mined to maximise the cash flow for that period. The result is a cut-off grade that varies over time as each increment is mined. The approach is that the mining for each increment aims to maximise the value of the remaining resource.

This approach ensures that capital is continually spent developing the remaining resource to obtain the maximum present value. Camus identifies that time must be considered a variable, where changes over time (for example, the price changes) are considered for each increment. Therefore, while this approach does require the higher-grade portions to be mined first to increase the NPV, it does not keep the cut-off grade at a high level for the life of the mine. The cut-off grade will be recalculated for each new increment (Macfarlane, 2006). For the final years, the cut-off grade is purely a marginal one where no further costs are incurred with developing the ore body (Macfarlane, 2006).

The approach that the South African gold mines included in this study follow for determining the cut-off grade has elements of the Camus approach in the way that each year's planning starts with recalculating the cut-off grade that will be used for the cycle.

4.3.5 Geological cut-off grade

A geological cut-off grade is a grade that truncates a frequency distribution of in-situ grades or separates mineralised material into grade fractions (Pasieka & Sotirow, 1985). The primary purpose is to show the relationship between in-situ tonnages and the average grade profile of a mineral resource over a range of specified cut-off grades. These cut-off grades effectively classify a mineral resource into predetermined tonnage and corresponding grade fractions or blocks comprising the overall mineral Inventory. They do not make any presumption about the economic viability of such blocks or areas (Wimberger, 2004). For certain commodities like diamonds, the rock type (kimberlite) becomes the ore, and the country rock is the waste.

The narrow, tabular platinum deposits have far lower grade variation than the Witwatersrand gold deposits. A geological cut-off is also applied where the UG2 and Merensky Reef are all considered payable ore. An optimal cut (for very thick UG2) is practised, but generally, the shafts are managed so that while the overall grade is above the pay limit, the mine is viable (Maseko, 2018).

4.4 Mining Costs in Cut-off Optimisation Approaches

Mining costs included in the cut-off grade calculation are subject to much debate and may change throughout the project's life.

Whilst this list is not exhaustive, the following alternate cut-off grade cost approaches will be considered for this study:

- Planning cut-off grade;
- Operational cut-off grade (normal pay-limit); and
- Marginal cut-off grade.

The difference between the planning, operational and marginal cut-off grades is that costs are included or excluded from the cut-off grade calculation.

4.4.1 Planning cut-off grade

Whilst a company is still recovering the initial capital costs, a planning cut-off grade can be used. This cut-off grade is determined to ensure that at least a return is obtained equal to the investment hurdle rate (Pasieka & Sotirow, 1985). This cut-off grade will include the mining costs and an additional percentage to quickly recover the initial capital costs (Hall, 2014).

4.4.2 Operational cut-off grade

The minimum in-situ or head grade of mineralised material that must be extracted from a deposit over a specified time horizon to generate net revenues equal to out-of-pocket expenses, including direct and indirect extraction, processing, and marketing costs, as well as minor ongoing capital expenditures, is known as an operational cut-off grade. (School of Mining Engineering, 2021a). The fundamental goal is determining which ore from the mining resource can be economically mined. It divides the overall resource into reserves and remaining resources, further divided into sub-economic and uneconomic categories.

It establishes the lowest grade of ore that must be delivered from working places such that the eventual revenues derived from there will cover the total working costs incurred in generating that revenue.

4.4.3 Marginal cut-off grade

In the final stages of the mine, development costs are minimal, and certain areas can be mined that were previously considered below the cut-off grade (Border, 1991). This is called a marginal cut-off grade (Pasieka & Sotirow, 1985; Hall, 2014). A marginal cut-off grade is the minimum in-situ or head grade of mineralised material delivered for further treatment. Certain costs are excluded as it is assumed these will be covered by more profitable material. The primary purpose is to specify the minimum acceptable grade of a mineral resource or reserve, which must be extracted to cover the direct extraction, processing and marketing costs when there is spare milling capacity towards the end of the mine’s life (Kalitenge, 2021).

4.4.4 Summary of cut-off grade cost approaches

Table 4-1 summarises the costs included for the planning, operational and marginal cut-off grade approaches.

Table 4-I. Costs included for the planning, operational and marginal cut-off grade approaches (School of Mining Engineering, 2021a).

	Planning	**Operational**	**Marginal**
Direct unit cost	X	X	X
Fixed cost	X	X	
Initial capital	X		
Ongoing capital	X	X	
Development	X	X	
Royalty	X	X	
Taxation	X		
Hurdle rate	X		

The operational cut-off grade approach uses reasonable costs for the mines included in this study (mature mines where the initial capital has been recuperated).

4.5 Royalty Costs in Cut-off Optimisation Approaches

The introduction of the mineral resource royalty has increased costs as it is payable on the revenue from the sale of the commodity, not just on the profits generated by the sales. This leads to increased mining risk because even if the mine makes a loss, there is still a payment due to the State.

A 'good tax' should not disturb economic behaviour and thus should be neutral (Mangondo, 2006). Income tax is calculated on profits and therefore does not alter economic behaviour as making a profit is considered a primary objective of any mining business (Otto et al., 2006). While the mineral resource royalty can be regarded as efficient, equitable, stable, transparent and sustainable, it is not considered neutral because the implementation of the tax alters the cut-off grade calculation. This determines what portion of the ore body can be regarded as economically viable (Cawood, 2011) and affects the published Mineral Reserves.

When reviewing the literature regarding the cost implications of royalties, Lilford (2017) considered the Australian situation and presented a gold case study where he reviewed the quantitative impacts of mineral royalties on mineral projects. However, studies of this type are rare. Furthermore, no comparable studies considered how variable mineral resource royalty costs should be considered for the cut-off grade optimisation.

4.6 Cut-Off Grade Optimisation Models

Companies can use some 'optimiser' program that utilises the block listing and the primary inputs to calculate the cut-off grade. The grade-tonnage curve is automatically generated – indicating how much material is available above the cut-off grade. The AMG is also then obtained. This AMG is the average grade of the material above the cut-off grade and becomes the planning grade. This can be visually represented on a grade-tonnage curve, as shown in Figure 4-1.

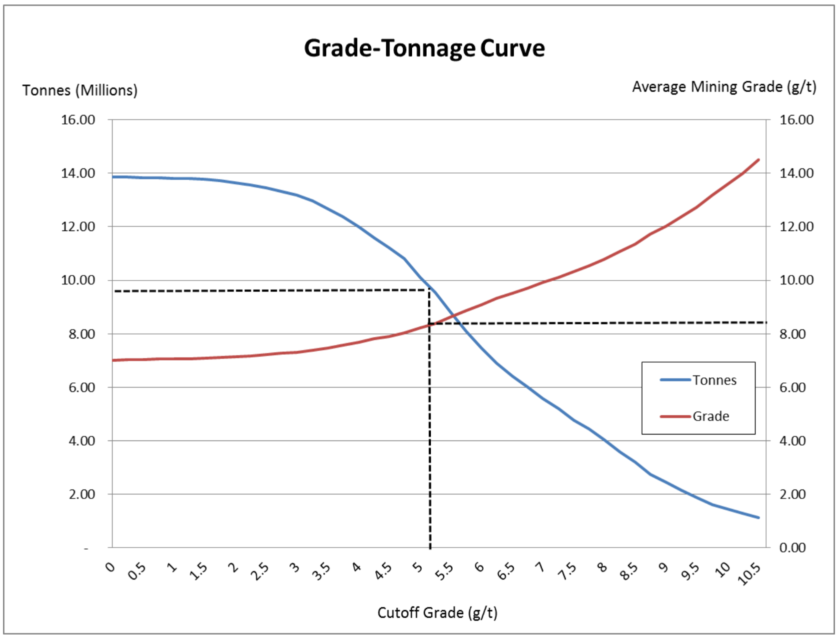

Figure 4-1. A typical grade-tonnage curve with a cut-off of 5.25 g/t. The resultant tonnes above 5.25g/t are 9.5million tonnes, and the AMG is 8.4g/t (Birch, 2016b).

As shown in Figure 4.1, the AMG and tonnes above the cut-off grade change as the cut-off grade is altered. The operational cut-off grade calculation is essentially straightforward. It determines the grade required for an ore unit to return a profit. It is essentially a break-even volume calculation where the volume is known (usually limited due to shaft capacity, mill capacity or some other physical constraint), and the unknown is the in-situ grade of the commodity. The other parameters required are total fixed cost and unit variable cost (UVC). The total unit cost (TUC) can be obtained (typically expressed in Rands/tonne for the South African mining industry). Another factor required for the cut-off grade calculation is the MRF - which is the MCF multiplied by the PCF. The commodity price in Rands/gram (converted from the quoted US$/oz using the exchange rate). These are all estimates and are subject to variation throughout the cut-off grade period. This forward-looking uncertainty adds to the financial risk to the investors if they change significantly.

A more advanced method for determining the cut-off grade is to do block listings for each ore body. The block list contains gold grades in grams/

tonne (g/t) or accumulated value (centimetre grams/tonne or cmg/t), the channel width (CW), stoping width (SW) and area of the blocks. The tonnage for each block from the area, SW, and specific gravity can be determined. A simple ore flow calculation determines the tonnage ratio from stope faces compared to all the tonnage milled. This calculation considers face tonnage, dilution, historical discrepancies, and how much development waste will be hoisted and milled as 'ore'. The ore flow also uses the historic MCF and PCF to calculate the planned MRF used in the financial model. Revenue is derived from the recovered gold, the planned gold price and the expected exchange rates. The mining costs can be estimated by considering the fixed and variable costs for the mine, considering the expected production rate, and the resultant profit for each block can be determined (Birch, 2016b). The grade-profit curve demonstrates this in Figure 4.2.

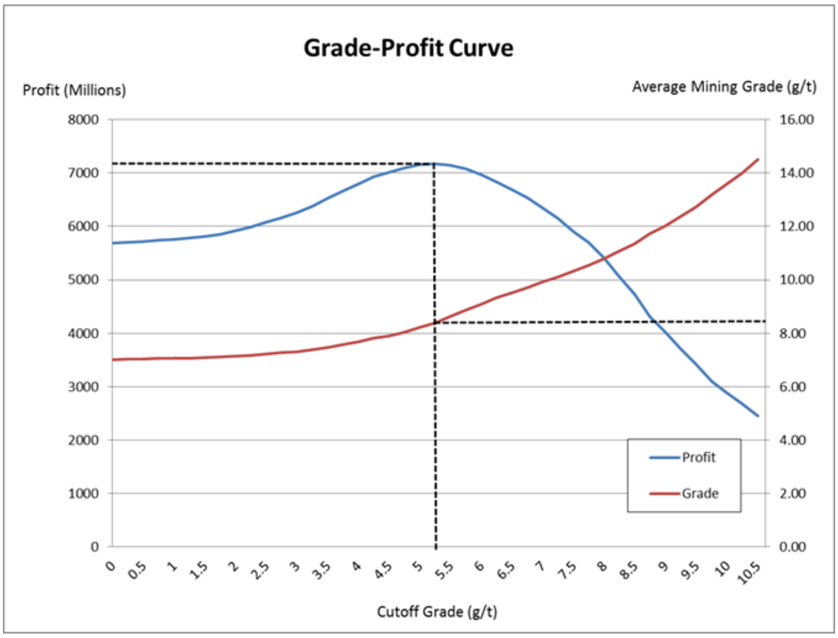

Figure 4-2. Typical grade-profit curve. The profit peak is at a cut-off grade of 5.25 g/t. The total profit is R7 173, and the AMG is 8.4g/t (Birch, 2016b).

Harmony followed a franchise model for managing its gold mines called the "*Harmony Way*". Part of the management philosophy was to use a common cut-off grade approach, which included using an in-house "*optimiser*" to calculate the cut-off grade for all their narrow tabular orebodies (Harmony, 2001). This optimiser uses Visual Basic and Excel. The author is familiar with this optimiser and has used it extensively. The optimiser requires the following as inputs to calculate the cut-off grade:

- The block listing with the measured resource blocks (per shaft section and per reef being evaluated);
- An assumed gold price;
- Planned production rates;
- Planned working costs (Rands per tonne); and
- The mine recovery factor (MRF) is equivalent to the MCF multiplied by the PCF.

Harmony has been using their optimiser program for approximately 20 years, based on in-house geology work in classifying orebodies. This approach to cut-off grade optimisation inspired the financial optimiser (the BirchOptimiser) developed for this study, although the mechanics of the two models used are entirely different. The Harmony optimiser determines the break-even grade only. It does not fulfil the needs of this study because there is no provision to explore the interaction of the royalties and income tax on cut-off grades.

Minnitt looked at how Lane's cut-off grade calculations were adapted to Wits-type gold mines in 2004 and found that applying the NPV criterion for determining and optimising value in mining operations was limited. He considered NPVs at various points in the value chain (mining, processing and marketing) to determine a balanced cut-off grade (Minnitt, 2004). Both Lane and Minnitt consider the NPV calculated over the life of the mine rather than short-term profitability as the primary measure of value. The cut-off grade optimised for NPV is higher than that obtained when optimised for profit. Due to discounting, the NPV optimisation model favours high-grading mining. This results in a shorter LoM and less mineral resource extraction (Birch, 2016b).

The discount rate used to calculate the DCF and resultant NPV are critical to the cut-off grade calculation. This discount rate is essentially the cost of capital and is usually calculated by the weighted average cost of capital (WACC). This WACC considers all the sources of money required for a project (equity and debt), the portion of the total each source makes and its cost. The various sources are then weighted by proportion, and an average is calculated. According to Smith et al. (2007), real discount rates of 9%–12% for mining projects are appropriate for South African mining projects. This is equivalent to 14.5 %–17.6 % at a 5% annual inflation rate for WACC in nominal terms (Smith et al., 2007). It is noted that Harmony indicates in their 2021 Annual Report that the real discount rates range between 8.9% and 11.1% (for 2019) for the South African assets (Harmony, 2001). Sibanye-Stillwater uses real discount rates of 6.7% to 10.0% (2019) for the South African gold assets (Sibanye-Stillwater, 2021).

Optimising NPV can drive decision-making to focus on short-term gains at the expense of the longer term. Thus, companies often use the total undiscounted cash flow (Hall, 2014). By optimising cut-off grade in three dimensions (cut-off grade, value and production rate) rather than the traditional two dimensions (cut-off grade and value), Hall identifies the 'peak of value' as shown in Figure 4-1. This approach gives mine planners an additional parameter to consider in determining the optimal cut-off grade (Hall & Hall, 2006; Alford & Hall, 2009). This peak of value needs to balance the economies of scale with Ricardo’s law of diminishing marginal returns (Brue, 1993; Boyce, 2021) dictated by the constraints of the mining environment (for example, hoisting and milling capacities, which would require significant expansion capital to add volume once their maximum current capacity is reached).

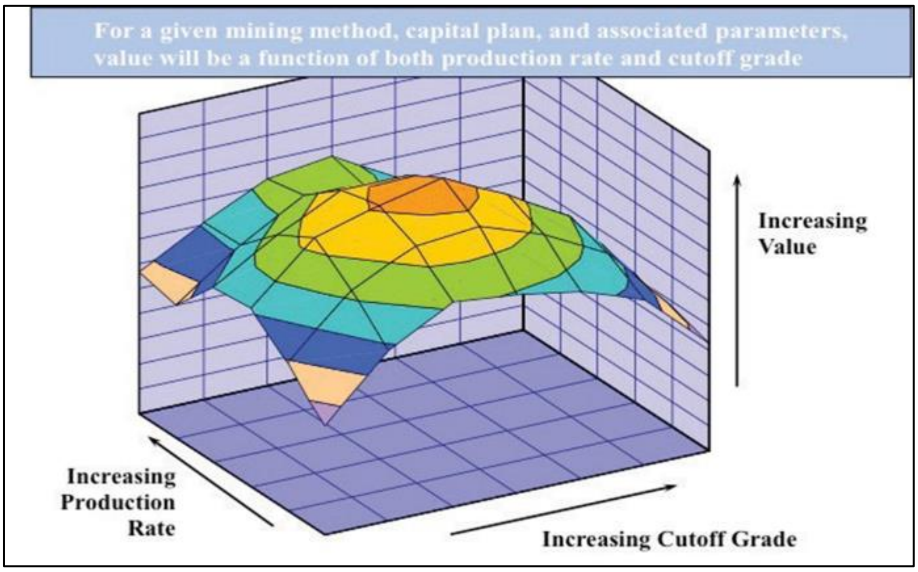

Figure 4-3. Peak of Value. This approach recognises the effect of volume on costs and the benefits of increasing the production rate to reduce unit costs (Hall & Hall, 2006; Alford & Hall, 2009).

The Lerchs-Grossman algorithm uses a graph-theoretic technique to optimise the pit shape and limits to maximise profit (Lerchs & Grossman, 1965). Whittle has expanded on this concept, brings in the time-value of money (TVM), and focuses on optimising the NPV (Whittle & Whittle, 2007). The Whittle Optimiser is predominantly applied in the open-pit environment, but Whittle is developing underground mine optimising. In the underground environment, bottlenecks are present. These can be in the form of a shaft or decline volume, plant volume, development metres, haulage limits, ventilation, traffic or working face congestion (Whittle, 2015). There are numerous examples in the literature of how this method is applied, and it is well understood by mining engineers worldwide (Akisa & Mireku-Gyimah, 2015).

The optimisation of the cut-off grade with the view of optimising the NPV has been established by Bascetin and Nieto using Visual Basic within Excel (Bascetin & Nieto, 2007b). Constructing a cut-off grade optimiser model using the Excel-based mixed-integer linear programming (the Solver) function is straightforward. This model can link the mine ore flow, resource block listing and cash flow models. Optimising output is either the profit or NPV by changing the cut-off grade. The varying cut-off grade alters the percentage of tonnes above the cut-off grade, and AMG feeds into the cash flow model (Birch, 2016b).

All the reviewed approaches to cut-off grade optimisation identify the value as either profit or NPV.

4.7 Recent Advancements in Cut-Off Grade Optimisation

Musingwini, in the 2016 Southern African Institute of Mining and Metallurgy Presidential Address, reviewed commonly applied optimisation techniques for underground mines. He noted the need to develop integrated stochastic optimisation that can be used in real-time (Musingwini, 2016). Other researchers have also identified shortcomings in the current approach to optimising mine planning, including determining the cut-off grade.

Numerous studies have been conducted in this field, and various innovative methods increase the value of mines. Napier looked at the effect of cost and price fluctuations and how these affect determining the optimum cut-off grades (Napier, 1983). In 1997, Wood looked at how the cut-off grade impacts the risks associated with mineral exploitation in the South African platinum industry (Wood, 1998). Lane et al. have considered the 'peak of value' and applied dynamic financial analysis (DFA), which aims to assess the risk element of the assumptions made for considering volume versus cut-off grade decisions (Lane, Sasto & Bondi, 2007). These address one of the main shortcomings of traditional approaches to cut-off grade determinations. The planning estimations of costs, grades, recoveries, and prices can differ from the actual values when mining occurs.

The development of complex computer modelling has allowed greater sophistication in determining cut-off grades. Azimi et al. (2011) list operational control theory, stochastic dynamic programming, non-linear programming, linear programming, genetic algorithm, and artificial intelligence methods (Azimi, Osanloo & Esfahanipour, 2011). However, whether these approaches have been widely applied to mining operations is questionable. It is recognised that a single cut-off grade for the entire mine is very limited, and developments in geometallurgy (Turner-Saad, 2011) and area costing have given rise to optimisation of cut-off from various regions of the mine, as well as from different geological domains. Future developments in mine planning, which could also be applied to cut-off grade optimisation, include multiple-criteria decision analysis (Mahase, Musingwini & Nhleko, 2016).

Hall published Cut-off grades and Optimising the Strategic Mine Plan in 2014, a comprehensive study of the various techniques currently used in the mining industry. It includes multiple value measures, including optimising the DCF and NPV (Hall, 2014).

Wood and Wimberger have investigated cut-off grades in the South African platinum industry. Wood described shortcomings of using cut-off grades, particularly regarding risk (Wood, 1998). Wimberger looked at extraction factors using various cut-off grades on the Merensky Reef (Wimberger, 2004).

The optimisation of the cut-off grade with the view of optimising the NPV has been established by Bascetin and Nieto using Visual Basic within Excel (Bascetin & Nieto, 2007b). This approach, however, has not considered the impact of the mineral resource royalty on the NPV.

Githiria and Musingwini (2019) have developed a stochastic cut-off grade optimisation model called NPVMining. They have identified that the common heuristic approaches fail to capture the uncertainty in the input parameters. These include the commodity price and the grade-tonnage distribution. The NPVMining model generates multiple cut-off grade policies, and thus the optimal approach can be selected. They have demonstrated that the approaches where the consideration of uncertainties associated with commodity prices and grades is ignored could negatively impact mining projects' economics.

4.7.1 Multiple-criteria cut-off grade

The literature noted that cut-off grade optimisation approaches consider multiple aspects in determining the optimal value. These approaches are used with multiple metals in the deposit (Ataei & Osanloo, 2003) or significant uncertainty with some assumptions (Azimi, Osanloo & Esfahanipour, 2013). Ahmadi developed a MATLAB software model to apply Lane’s theory and balanced the limitations of the mining, processing and refining phases. Using a multiple-criteria approach, he showed a significant improvement in the NPV of an open-pit iron ore mine (Ahmadi, 2018).

All the multiple-criteria approaches reviewed focused on improving the profit or NPV. This approach is also found predominantly applied in the open-pit environment.

4.7.2 Area and mining method cut-off grade optimisation

Meredith (2021) considered how separately costing different mining methods could be used in an underground South African gold mine to increase the overall extraction of the ore body. His study identified mine areas where costs significantly differ from the overall average mining cost. He applied activity-based costing to these areas and demonstrated how some areas with grades below the mine-wide cut-off grade could be extracted economically (Meredith, 2021).

On the Harmony mines, area costing is widely applied. Due to different mining depths across the operation and vastly different distances from the shaft areas, the mining efficiency varied. Certain ore body types also had different MRFs than those used in the mine-wide cut-off grade calculation.

Considering these differences, some areas could be mined profitably using an area cut-off grade rather than the mine-wide cut-off grade. However, Meredith noted that this approach is challenging to apply without detailed area costing information. He applied Monte Carlo simulation (using @Risk software) to consider the uncertainties in the costing estimations and still showed that overall value could be added by the area costing approach (Meredith, 2021).

4.8 Review of Cut-Off Grade Methods Used in Southern Africa

The author published a review in Resources Policy (*Review of cut-off grade optimisation from Southern African mines. Student assignment based observations)*(Birch, 2018).

Mineral Resource Management Master of Science (MSc) students were required to do an assignment on their operations to investigate the cut-off grade approach. As part of the research, they were required to identify how this cut-off grade was optimised and if the primary value driver was profit or NPV.

Forty-five assignments represented South Africa, Zimbabwe, Namibia, Botswana, Lesotho, and the Democratic Republic of the Congo. The commodities are gold, platinum, diamonds, coal, copper, iron ore, manganese, zinc and chrome. Only the assignments, which received a passing grade, were included in the assessment.

Some commodities and mining methods lend themselves to cut-off grade optimisation. However, it is noted that many mines focus on determining the cut-off grade just on the primary break-even grade and Lane's algorithm and do not optimise the cut-off considering other factors like volume or NPV. There is some evidence of optimisation considering the volume/cost relationship to identify the 'hill of value'. The Whittle Optimiser and the

Lerchs-Grossman algorithm are applied for some of the open-pit mines reviewed, and the optimisation is focused on the NPV. Fundamentally, and perhaps expected, few of the latest optimisation approaches are used on the mines at the operational level reviewed by this exercise (Birch, 2018).

4.9 Chapter Summary

This chapter has reviewed the basic concepts and definitions of cut-off grades. Furthermore, it reviewed the different cut-off grade optimisation approaches in the literature. It has been noted that there is no definitive way to consider the mineral resource royalty in the cut-off grade estimation. The South African mineral resource royalty is unique in that there is no set rate, but it depends on the profitability. This poses some challenges in how this cost needs to be considered in optimising the cut-off grade.

It has been determined that an easy-to-use cut-off grade optimisation model needs to be developed to determine the impact of the mineral resource management that will suit the objectives of this study. This model will run six options regarding how companies can consider the mineral resource royalties outlined in the introduction chapter and how these affect the cut-off grades. The development of this optimisation model includes the lessons obtained through this literature review and is described in Chapter 5.

5 CUT-OFF GRADE OPTIMISATION MODEL

5.1 Introduction

Mining companies calculate a cut-off grade to determine which portion of the mineral deposit can be mined economically. These cut-off grade calculations are described in Chapter 4. For the annual planning cycle, a cut-off grade needs to be established to determine the areas included in the mine plan.

The initial study was published in 2016. *The impact of South African mineral resource royalty on cut-off grades for narrow, tabular Witwatersrand gold deposits* (Birch, 2016a)*.*

This initial study aimed to understand the impact of the mineral resource royalty costs on cut-off grades. Furthermore, the study aimed to determine how mines consider these costs when calculating their cut-off grades. This initial study focused on six gold mines. For this study, the available cut-off grade optimisation approaches were considered (covered in Chapter 4), and none were deemed suitable to answer the specific questions raised in the context of narrow tabular South African gold mines. The South African mineral resource royalty and the gold tax formula used to determine the income tax rate are unique, considering they both have rates determined by profitability. This should be taken into account when optimising the cut-off grade.

The one key finding from the initial study is that the mines investigated include the estimated royalty cost as a mining cost when calculating the cut-off grade. Their approach calculates the simple break-even grade and uses this value as the cut-off grade. This approach affected the cut-off grade negatively, and in some cases, the direct revenue (royalty and income-tax revenue) to the State was reduced by introducing the royalties. This method is considered the base case compared to the various approaches investigated in this study.

This chapter outlines the development of a financial optimiser (the BirchOptimiser to differentiate from other optimiser models discussed previously). This BirchOptimiser can compare the different proposed approaches for considering the royalty costs. The best approach for considering the royalty costs considering the profitability component of both it and the gold tax rate is then identified in the following chapters. The construction of the key elements of the BirchOptimiser is presented in Appendix 1 so that it can be replicated to confirm the validity of the approach followed for cut-off grade optimisation.

5.2 The Basic Break-Even Model

The BirchOptimiser performs two functions. The first function is to determine the break-even cut-off grade considering the block listing, ore flow and mining costs (with the various options of considering the mineral resource royalty costs). The second function is a financial optimiser that uses the Excel Solver function to optimise the cut-off grades. The difference between the optimised cut-off grades can then be compared to the break-even cut-off grades to determine how companies should consider the cost of mineral resource royalties. The BirchOptimiser is also used to explore the impacts of:

- Changes to how gold mine income tax is calculated;
- The NPV and the impact of discount rates;
- The impact of the block size on grade-tonnage curves; and
- The impact of grade estimation uncertainty on cut-off grades.

The BirchOptimiser is also used to explore how value can be optimised considering different stakeholder groups in the mining industry. These aspects are considered very significant and are presented in Chapter 8.

The BirchOptimiser model comprises three Excel spreadsheets. These sheets are:

- The block listing;
- The cash flow; and
- The ore flow (for this study, only the required information from the ore flow has been entered into the model).

An additional sheet was added to create graphs, but this is not essential for determining the break-even and the optimised cut-off grades. Examples of the graphs created are used in Chapter 7 to display the differences in AMG and tonnes above the cut-off grade between the base case and optimised cut-off grade approaches.

5.2.1 The block listing

This block listing is created from the geological model and lists all the potential mining areas, estimated grades and volumes. Based on this block listing, companies declare their Mineral Resource and Reserves into the public domain. A grade-tonnage curve is usually part of the annual report when a competent person's report is prepared as shareholders and potential investors require. This figure makes it easy to visually estimate the tonnes above a specific cut-off and the resultant average grade of all those blocks above that cut-off grade.

Some companies model accumulation value (cmg/t) rather than grade (g/t). Cmg/t is helpful for very narrow orebodies because it gives the content rather than just the grade over the mineralised width. The cmg/t is calculated by multiplying the grade of the sample with the width the sample represents. Multiple samples are taken and composited when sampling narrow tabular orebodies to get the average grade over the mineralised width. Each sample grade is multiplied by the width (in centimetres), and all the individual values are added together. This combined value is then the value in cmg/t. This value can then be divided by the expected mining width, and the average mining face grade of the block can be determined. A 1,000 cmg/t over 1 metre will result in a face grade of 10 g/t. It is possible then to compare the metal content with a very narrow 1cm mineralised zone with 1,000 g/t (for example, the carbon-rich facies of the Basal Reef) to one with a 100 cm mineralised width with a grade of 10 g/t. Both faces will have the same mining face grade of 10 g/t if the minimum mining width is 100 cm.

A typical block listing obtained from a narrow tabular precious metal mine will have the following values:

- A unique block number;
- Mineral resource classification (Measured, Indicated or Inferred);
- Grade in g/t or accumulation value in cmg/t;
- CW;
- Area (in m^2); and
- SW.

The unique block number usually contains information about the ore body type and the particular shaft area in which the block is located. This information is beneficial if the cut-off grades are applied to specific shafts, ore bodies, or mine levels. Area costing is a well-developed concept in the South African mining industry, and the more accurate costs can be assigned to specific areas, the greater the understanding of each area of the mines' contribution to the overall financial picture can be obtained (Meredith, 2021).

The accepted practice for the declaration of Mineral Reserves (Proved and Probable) is only to declare the blocks classified in the Measured and Indicated Mineral Resource categories (Lomberg & Rupprecht, 2017). For this study, the same principle will be applied, and only the Measured and Indicated blocks will be considered when running the various block models through the BirchOptimiser and the other models.

From the block area and CW, the in situ tonnage for each block can be determined using Equation 6.

In situ tonnage (ist):

$$ist = a * CW * RD \quad \text{Equation 6.}$$

Where: a is the area in m^2, CW is the channel width, and RD is the relative density.

If the area is measured horizontally and the ore body is dipping, a dip factor is applied to the area to correct for this. It is the corrected area that is used in Equation 6.

The mining tonnage for each block can be obtained using Equation 7.

Mining tonnage (t):

$$t = a * SW * RD \quad \text{Equation 7.}$$

Where: a is the area in m^2, SW is the stoping width, and RD is the relative density.

The SW can be obtained from the CW by adding the expected mining dilution. A minimum mining SW can be determined for very narrow ore bodies. An example of this type of formula is expressed in Equation 8.

Stoping width (SW):

$$If\ CW > 100, SW = 100 + 20;\ If\ CW < 100,\ SW = 120 \quad \text{Equation 8.}$$

Where: CW is the channel width in cm and SW is the stoping width in cm.

The mining grade is obtained from the in situ cmg/t grade divided by the SW. This is expressed in Equation 9.

Mining grade (g/t):

$$g/t = cmg/t \div SW \qquad \text{Equation 9.}$$

Where: cmg/t is grade, and SW is the stoping width.
The mining grade is expressed in g/t.

The metal content from each block can be determined using Equation 10.

Metal content $Au(g)$:

$$Au(g) = g/t * t \qquad \text{Equation 10.}$$

Where: g/t is the mining grade over the mining width (in cm), and t is the block mining tonnage. The content $Au(g)$ is measured in grams.

For the early part of the development of the model, additional columns were added to the block listing to show the expected grams of metal produced (Equation 11), revenue (Equation 12), cost (Equation 13) and profit (Equation 14) from each of the blocks.

Metal produced from a block (g):

$$Au(g) = g/t * t * MRF * sr \qquad \text{Equation 11.}$$

Where: g/t is grade over the planned stoping width, t is the tonnage at the expected stoping width, MRF is the metal recovery factor, and sr is the ratio of stope to milled tonnage. The content Au(g) is expressed in grams.

Revenue from a block (rev):

$$rev = m * p \qquad \text{Equation 12.}$$

Where: m is the metal expected to be produced from the block (in grams), and p is the price (in US$ per gram). The revenue (rev) is measured as US$.

Mining cost for a block (mc):

$$mc = t * TUC \qquad \text{Equation 13.}$$

Where: t is the tonnage at the expected stoping width, and TUC is the total unit cost (based on AISC in US$/tonne). The mining cost (mc) is expressed in US$.

Profit for a block (p):

$$p = rev - mc \qquad \text{Equation 14.}$$

Where: rev is the expected revenue, and mc is the cost (both in US$). The profit (p) is measured in US$.

Whilst these additional columns were used in some of the early analyses of cut-off grade models and testing the final model, they are unnecessary for running the evaluation models used in Chapter 7. The block list can be sorted using the profit (Equation 14) column to determine the basic cut-off grade tonnes above cut-off grade and AMG. All the blocks with a positive profit can be selected, and their tonnage added, as can their metal content (Equation 10). The AMG will be the total metal content divided by the total tonnage. This approach does not optimise considering the interplay between the mineral resource royalty, gold tax formula, and profitability rates.

Various block listings obtained directly from mines have been used for previously published research papers (Birch, 2016a,b, 2017, 2018).

However, block listings have been simulated from the published grade-tonnage curves for the analysis covered in this thesis. Mining companies do not release the raw block listings into the public domain as part of their annual Mineral Resource and Reserve declarations, only the resultant grade-tonnage curves.

5.2.2 The ore flow

Mine surveyors measure and record waste and ore broken underground, as specified in the ore flow calculations. All tonnages from various sources, including surface stockpiles, are combined to compare the actual tonnage received at the processing facility.

The ore flow document is produced monthly and records all ore and waste source values. For this study, two values are essential and determined from the ore flow document. The first figure is the MRF and the second is the ore ratio from the stope faces compared to the total tonnage milled. Some of the companies publish a milled width (MW) figure. This figure is the total milled tonnage divided by the stope area and gives an alternative method to determine the ore ratio from the stope faces compared to the total tonnage milled.

Mine recovery factor

The MCF is the ratio, expressed as a percentage, of the specific product accounted for in the recovery, plus residues and the corresponding product called for by the mine's measuring and evaluation methods (Storrar, 1981). The objective of the MCF is to determine the efficiency of the mine processes. In an ideal world, the MCF must be as close as possible or equal to 100%, a situation that is impossible in practice when blasting and transporting ore (Xingwana, 2016). An MCF of 85% is considered reasonable for gold mines (Xingwana, 2016). MCFs closer to 100% are more likely found in platinum mines.

The difference between 100% and the calculated MCF comprises a combination of real loss and apparent gain/loss (De Jager, 1997). Any MCF investigation should first focus on the apparent gain/loss to ensure that the estimations of the metal called for are as close to the actual value as possible. This investigation will prevent the typical response of “how do you know it was in the ground in the first place”. De Jager (1997) focused on finding the missing physical metal at Western Holding Gold Mine. He concluded that most of the metal was not in the ground, and the most significant contribution to the low MCF on the mine was poor estimations (apparent losses).

The mines’ survey departments also calculate the MRF, essentially the MCF excluding the residues. It can be expressed by Equation 15.

Mine recovery factor (MRF):

$$MRF = (r \div cf) * 100 \qquad \text{Equation 15.}$$

Where: r is the metal recovered, and cf is the metal called for. Both are measured in grams, and the MRF is expressed as a %.

The MRF, rather than the MCF, is required for the break-even grade calculation. The MCF accounts for the metal not recovered by the plant and is in the residue. No plant is 100% efficient, but the surveyors know the metal is in the tailings dam and can account for it. This is the fundamental difference between the MCF and the MRF. Metal in the tailings dam cannot be sold and does not contribute to the mines’ revenue. Figure 5-1 shows a typical ore flow document from a South African gold mine.

		12 Month ave			
		%	m / m² / tons	g/t	Grams
RD	2.72				
CUT-OFF CMG/T			927.105		
Stope Reef cmg/t based on current samp (3 decimals)			1310.136		
Cmg/t below cutoff based on current samp			708.949		
Cmg/t above cutoff based on current samp			1535.090		
SW (excl. Gullies, **incl. Recl.**) (3 decimals)			140.426		
SW (excl. gullies, **excl. M^3 Recl.**)			140.426		
FACE REEF G/T				9.33	
Face Grade (incl dilutions, excl gullies) cmg/t			1295.246		
Face Grade (incl dilutions, excl gullies) g/t			9.22		
Reef M^2 below cutoff based on current sampling			4287		
Reef M^2 above cutoff based on current sampling			11458		
TOTAL REEF M^2 (excl. fault, dykes, os M^2)			15745		
Off Reef M^2 (Off reef mining) (excl faults/dykes) OS M^2			181		
Total M^2 (Reef M^2 + OS M^2) Excl fault/dykes			15926		
STOPE REEF TONS (excl. M^3 Recl)		100.00	60139	9.33	561078
GULLY DILUTION TONS		4.17	2510		
WASTE / OFF REEF STOPING TONS		1.15	690		
Dilution in stopes (Flt, Dyke, Off Reef mining)			690		
Equiv m^2(reef+fault+waste+converted)			16104		
RECLAMATION / CUBIES / etc. (M^3 TONS)		0.00	0		0
TOTAL STOPE TONS		**105.32**	**63338**	**8.86**	**561078**
DEV. REEF TONS BROKEN		2.60	1564	4.04	6321
Extra Waste Tons from Reef Dev		1.28	770	0.00	0
TOTAL ORE TRAMMED		**107.92**	**64903**	**8.74**	**567399**
VAMPING OLD GOLD TONS		3.59	2157	5.49	11844
DEV. WASTE TONS TO MILL		0.62	373	0.00	
FLUSHING TONS		8.60	5172	0.00	0
ADD U/G SOURCES TO MILL (Qual + Mud)		6.69	4022	0.41	1664
AVAIL FOR HOISTING (Survey Call)		**127.42**	**76626**	**7.58**	**580906**
DISCREPANCY		-2.41	-1449		
TOTAL TONS HOISTED		**125.01**	**75177**	**7.73**	**580906**
TOTAL TO PLANT		**125.01**	**75177**	**7.73**	**580906**
MILL BINS / SILOS - BEGIN +		10.98	6606	12.21	80672
MILL BINS / SILOS - END -		10.74	6456	12.27	79219
TOTAL INVENTORY BEGIN		10.98	6606	12.21	80672
TOTAL INVENTORY END		10.74	6456	12.27	79219
TOTAL TONS MILLED		**125.25**	**75326**	**7.73**	**582359**
CHECK		125.25			
MCF (3 dec) GAF / Available for Hoisting		70.129			
SCF (Shaft Gold Delivered Dry / Available for Hoisting		67.83			
PCF (GAF/Shaft Gold Delivered Dry) also (MCF/SCF)		103.396			
PRF (3 dec) Gold Rec / GAF		95.792			
MRF (3 dec) MCF x PRF		67.18			
GOLD RECOVERED			**75326**	**5.18**	**390241**
RESIDUE			75326	0.23	17144
GAF Recovered + Residues			75326	5.41	407384

Figure 5-1. Example of a 12-month average ore-flow document from a gold mine. Note that 'tons' are metric tonnes. (Source: Harmony Gold Mining Company).

It can be observed in Figure 5-1 that 561,078 tonnes come from the stopes whilst the total tonnage milled is 582,359. The ratio of stope to milled tonnes is 96%. The MCF, in this case, is 70.13%, whilst the MRF is 67.18%.

Mhlongo (2021) questioned the accuracy of the survey call values and determined that a ±2% variance (at a 95% confidence) is possible in the 12-month average MCF, even though this figure is generally reported to one or two decimal places (and published in the annual Mineral Resource and Reserve reports). This study estimated the possible variance with each of the estimations in the survey ore flow document and then applied Monte Carlo simulation to determine the overall variance in the annual MCF values. The study was conducted on the gold mines of the Sibanye-Stillwater Group (Mhlongo, 2021). Various studies have been conducted on the impact of poor sampling on gold mines and their contribution to low MCFs (Fourie & Minnitt, 2016).

Physical metal loss in gold mines is attributed to excessive water use, poor fragmentation (Xingwana, 2016), unaccounted dilution, and theft.

5.2.3 The cash flow

The third Excel sheet of the model is the cash flow. The cash flow used in this study is modelled on the example used for the mine financial valuation courses and is relatively simple (School of Mining Engineering, 2021b). The core components are:

- Production;
- Revenue;
- Costs;
- Earnings before interest and tax (EBIT);
- Capital costs and tax shield;
- Mineral resource royalties;
- Income tax;
- Cash flow; and

- DCF.

Production

The production rate for this study uses the anticipated production rate for each mine established from the annual reports. The data obtained from the annual reports generally show the ore processed without how much is from the stope faces. The ore flow is used to determine the ratio of the ore milled, which comes directly from the faces (and so from the mineral resources) and other sources. Where companies publish the SW and MW, this ratio is considered the equivalent for this study if the companies' ore flow is unavailable.

The stope-face tonnes available to mine above the cut-off grade are determined from the block listing (Equation 7) using an Excel =SUMIF function. If the estimated grade of a block is above the cut-off grade, it is then included in the available tonnage. The AMG is determined from the sum of the metal content from the blocks (determined by Equation 10 from the block listing and using the same Excel = SUMIF function) divided by the tonnes above the cut-off grade.

The cash flow model is populated with the production assumed to continue until the mineral resource above the cut-off grade is depleted. This is determined by a simple Excel =IF statement where if the remaining tonnes exceed the projected annual tonnage, the total annual tonnage will be mined, or only the remaining tonnage will be mined. Once the tonnes are depleted, no more mining takes place. The model only includes the Measured and Indicated resource blocks – the Inferred resource blocks are not included.

The AMG is associated with the tonnage from the stope faces. The additional tonnage is considered dilution for this study and does not add additional metal for revenue generation. However, the costs need to be considered because they impact the overall milled costs required to input into the model. If these dilution tonnes were not considered, the stope mining costs would be understated, affecting the optimal cut-off grades.

The MRF is applied to the metal mined to determine how much is available to be sold and generate revenue.

The metal produced in the cash flow model is determined using Equation 16.

Metal produced $Au(oz)$:

$$Au(oz) = (AMG * ST * MRF) * 31.1 \quad \text{Equation 16.}$$

Where: $Au(oz)$ is the metal produced in troy ounces, AMG is the average mining grade, ST is the stope tonnes, and MRF is the mine recovery factor. The AMG is expressed in g/t, the ST in tonnes, and the MRF is a %.

Revenue

This study states the metal price and resultant revenue in US$ or ZAR. Due to the volatility of the ZAR and uncertainty of the exchange rates, US$ has been used.

The gold price used for this study is for 2021. The cash flows are in real monetary terms and use 2021 costs, so the gold price used is for the same period.

The formula to determine the gross sales revenue is as shown in Equation 17.

Gross sales revenue (GSR):

$$GSR = (Au(oz) * p) \quad \text{Equation 17.}$$

Where: $Au(oz)$ is the metal recovered in troy ounces, and p is the metal price in US$/oz.

Costs

Mining operational costs (OpEx) can be broken down into fixed and variable costs. The basic form of the cut-off grade formula (Equation 5) requires these two costs to be stipulated. However, the fixed costs are divided by the expected production to determine the unit fixed costs. This is then added to the variable costs to give the TUCs. For this study, the projected costs obtained from the various mines' do not break down into the core fixed and variable components. The costs are presented as unit OpEx costs (either US$/oz or US$/tonne).

Prior to 2013, gold mining companies reported their mining costs differently. Some companies' cost reporting only focussed on mining and processing costs to produce gold, ignoring critical elements such as sustaining capital (Yapo & Camm, 2017). Considering that the cut-off grade needs to cover replacing the mined ground, this type of costing approach is not valid for this study. The World Gold Council (WGC) developed a more consistent reporting approach, and these include the AISC and all-in costs (AIC) (Gianfrate, 2017). The WGC chose to exclude the following costs in the determination of AISC:

- Income tax;
- Non-sustaining capital;
- All financing charges (including capitalized interest);
- Costs related to business combinations, asset acquisitions and asset disposals; and

- Items needed to normalize earnings include impairments of non-current assets and one-time material severance charges (Yapo & Camm, 2017).

All the companies included in the study report their AIC and AISC. The AISC figure has been used for this study (Meredith, 2021), with the expected royalty costs deducted (because the model determines this from the formula built into it).

Because the AMG results from the cut-off grade, the US$/oz OpEx cannot be used for the model. US$/tonne OpEx is a more meaningful measure of the mines' production efficiency for this study and is thus used. The variation of the production rate and the effect on the cut-off grade is not considered when running these models (the peak of value as shown in Figure 4-3). The production rates published by the companies for their various individual mines are accepted as the optimal rate considering the constraints on the operations. The published data are accepted because a deeper understanding of the operation is required to identify potential obtained by removing these constraints to increase production and lower the US$/tonne OpEx.

Earnings before interest and tax

The EBIT is simply the gross sales revenue minus the total costs, as shown in Equation 18.

EBIT (US$):

$$EBIT = (GSR - TC) \qquad \text{Equation 18.}$$

Where: GSR is the gross sales revenue, and TC is the total costs in US$.

Capital costs and tax shield

The mines included in the study are all mature mines whose initial CapEx is considered recouped. The operational cut-off grade approach regarding the costs included in the study will be accepted.

Mineral resource royalties

The formulae for the South African mineral resource royalties are presented in Chapter 1 (Equations 2 and 3). For the gold mines, the refined royalty formula is applied. The refined rate is used for the companies with refineries for the platinum mining companies. The unrefined rate is applied for companies that only produce a precious metal concentrate.

Income tax

Most South African mines are taxed at the corporate tax rate of 27% (reduced from 28% from April 2022 (PricewaterhouseCoopers, 2022)). The gold tax formula is applied for the gold mines, as described in Chapter 1 (Equation 4). The mineral resource royalty is a tax-deductible cost that affects the taxable income amount for the corporate tax rate. Besides affecting the taxable income amount, the gold tax formula also affects the income tax rate. This interplay between the mineral resource royalty and the gold tax rates has necessitated this approach to the investigation as to which is the optimal approach to deal with the costs of the mineral resource royalty in determining the cut-off grades.

Cash flow

The cash flow is calculated for each year of production. The formula is as follows:

Cash flow (CF):

$$CF = (EBIT - MRR - it) \qquad \text{Equation 19.}$$

Where: $EBIT$ is the earnings before interest and tax, MRR is the mineral resource royalty, and it is the income tax in US$.

Discounted cash flow

The present value of expected future cash flows is determined using a discount rate to calculate the DCF (Investopedia, 2021a). The discount rate is determined using the company's WACC (School of Mining Engineering, 2021b). The WACC represents a company's average cost of capital from all sources. These include equities (common stock, preferred stock, and bonds) and other forms of debt. The cost of equity can be determined using various methods, including the capital asset pricing model (CAPM) and the Gordon growth model (GGM) (School of Mining Engineering, 2021b).

The formula for determining the DCF is as follows:

Discounted cash flow (DCF):

$$DCF = (CF_1/(1+i)) + (CF_2/(1+i^2)) + (CF_\mathrm{n}/(1+i^\mathrm{n})) \quad \text{Equation 20.}$$

Where: DCF is the discounted cash flow (US$), CF_1 is the cash flow for the first year, CF_2 is the cash flow for the second year, CF_n is the cash flow for additional years, and i is the discount rate (%) (Investopedia, 2021a).

The NPV is the difference between the present value of cash inflows and the present value of cash outflows over a period of time (Investopedia, 2021b).

5.3 The BirchOptimiser Model

The financial optimiser model created for this study uses the Excel Solver optimisation tool to determine the cut-off grade (see Appendix 1 for a complete description of the BirchOptimiser).

Excel Solver

The Excel Solver is bundled with Excel, a widely used optimisation program. Solver can be used to determine an optimal value (maximum or minimum) for a formula in a target cell that is constrained or limited by the values of other formula cells in a worksheet. Solver adjusts the values in the decision variable cell (the cut-off grade) to fulfil the constraint bounds of the cell and provide the desired result for the target cell (the profit or NPV) (Microsoft, 2022).

Solver has three algorithms that it uses, and these are:

- Generalized reduced gradient (GRG) nonlinear (for problems that are smooth nonlinear);
- LP Simplex (for linear problems);
- Evolutionary (for non-smooth problems)(Microsoft, 2022).

It has been found for the BirchOptimiser model that although the evolutionary approach is the slowest, it is the most reliable. It has been noted that the GRG approach gives inconstant results, often not changing the initial value input for the cut-off grade. The LP Simplex approach has not been tested because the nature of the model is not considered linear.

The BirchOptimiser determines the tonnage above the cut-off grade and the AMG from the block-listing sheet. The MRF and ratio between stope tonnage and total milled tonnage are obtained from the ore flow sheet. These values form the basic inputs into the cash flow sheet, the production rate, metal price and mining costs. As Solver's cut-off grade varies, the tonnage above the cut-off grade and AMG inputs change to maximise the target selected (profit or NPV).

The analysis of the optimal approach to model the costs of the royalties (Chapter 7) is achieved by:

- Setting the royalty costs to US$0;
- Setting the royalty costs to be 0.5% of the total revenue;
- Using the rate that was determined by the previous production year;
- Estimating the royalty rate based on the break-even cut-off grade and the resultant profitability ratio; or
- Assume that the highest rate will be applied depending on whether the mine applies the refined (5%) or unrefined (7%) rate.

The profitability optimisation model determines the mineral resource royalty rate automatically. This approach applies a variable rate depending on the profitability and determines if a higher profit is to be made even if the profitability rate is lower. This is compared to the five approaches presented above to identify the best approach to considering the royalty costs whilst optimising the cut-off grade. This analysis is presented in Chapter 7, while the results for the eleven mines included in the study are presented in Appendix 2. The construction and operation of the BirchOptimiser are described in Appendix 1.

5.4 Published Grade-Tonnage Curves

The geological block and mining block models are two critical elements of the mine planning process (SRK Consulting, 2018). These form the basis of the grade-tonnage curve and the financial model (Ronald, 2018). The data spacing guides the dimensions of the blocks for the geological block model. The sizes of the blocks in the mining block model are driven by the mining method and how selective the ore can be mined to minimise dilution (the SMU) (Hartman et al., 1992).

The block sizes used for the simulated block lists created for this study use predominantly 30 by 30-metres for the Measured and 60 by 60-metre blocks for the Indicated Resources. The Mineral Resources published in the annual company reports are based on these block sizes, which is critical to understand when considering the overall data presented in the study (Birch, 2019).

The block sizes used to determine the Measured and Indicated Mineral Resource published annually are far smaller than the SMU, especially in the deep and ultra-deep gold mines. The idea that the optimum block size considering the dilution associated with larger blocks was explored, and it was shown that if the average grade of mineral resource blocks is higher than the cut-off grade, it is beneficial to use larger block sizes. However, this is not the case when the average grade of the mineral resource blocks is less than the cut-off grade. Increased selectivity to reduce dilution is critical, so smaller block sizes are required.

The impact of the small blocks on the integrity of this study has been considered. The simulated grade-tonnage curves are developed to match the profiles of the published grade-tonnage curves. The overall in situ grades and tonnages must match the published grades and tonnages. This required the block sizes for the simulated block lists created for the study to match the published ones.

The core study presents production and financial values based on optimised cut-off grades, mineable tonnes, and AMG results. It is assumed that all the blocks above this cut-off grade can be mined (ore blocks), and the blocks below this cut-off grade will be classified as waste and left underground. It also assumes that all the ore blocks can be accessed individually, and no waste mining is required to access them. This is not the case in reality.

It is thus accepted that there will be a disjoint between the overall production results obtained for each of the gold mines included in the study compared to the published Mineral Reserves. However, this does not change the opinion that a study of this nature, which is to identify the optimal approach when considering the mineral resource royalty costs while calculating the cut-off grade, is still valid.

5.5 Chapter Summary

This chapter has presented the financial optimisation model, which has been developed for this study. Besides developing a tool to answer the core questions of this study (the impact of the South African mineral resource royalties and the optimal way companies should consider these costs whilst determining the cut-off grade), the model provides a unique approach to financial optimisation. The model utilises the Solver function built into Excel. This optimisation tool is straightforward and allows flexibility unavailable in other approaches. This approach also allows the development of a multiple-stakeholder decision analysis model, which optimises factors beyond just profit or NPV (Chapter 8). The following chapters present the mine data used in this study and then describe how this model identifies the optimal approach when considering the royalty costs in cut-off grade calculation.

6 MINE DATA FOR THE STUDY

6.1 Introduction

This chapter provides an overview of the tabular gold mines considered for this study. Not all the gold mines in South Africa mine tabular ore bodies and follow the cut-off grade approach, and as such, are not included. The focus is on the gold mines using conventional mining methods. Four gold mines have also been excluded from this study because their production and financial data are unavailable in the public domain, even though they practice narrow, tabular conventional mining methods.

The gold mines included in the study all belong to Sibanye-Stillwater and Harmony. Before 2020, Mponeng Mine was the last remaining underground AngloGold Ashanti in South Africa, but ownership was passed to Harmony. The mining costs are based on the 2021 data, whilst the resources used for the study are obtained from the companies' 2020/21 Mineral Resources and Reserves reports. Mponeng Mine has been included with the Harmony gold mines.

The following gold mines have been included in the study:

- West Rand Goldfield:
  - Doornkop Gold Mine (Harmony).
- West Wits Goldfield:
  - Driefontein Consolidated Gold Mines (Sibanye-Stillwater);
  - Kloof Consolidated Gold Mines (Sibanye-Stillwater);
  - Kusasalethu Gold Mine (Harmony); and
  - Mponeng Gold Mine (Harmony);
- Klerksdorp Goldfield:
  - Moab Khotsong Gold Mine (Harmony).
- Free State Goldfield:
  - Bambanani Gold Mine (Harmony);
  - Beatrix Gold Mine (Sibanye-Stillwater);

- Masimong (Harmony);
- Joel Gold Mine (Harmony); and
- Tshepong Gold Mine (Harmony).

6.2 South African Gold Mining Areas

South Africa has distinct gold mining regions where gold mining is still active. These include gold in the Witwatersrand Basin (East Rand, South Rand, Evander, West Rand, West Wits, Klerksdorp and Free State goldfields), as well as outside the Witwatersrand Basis (Barberton Greenstone Belt, Transvaal Drakensberg, Murchison Greenstone Belt, Amelia-Kraaipan Greenstone Belt and the Transvaal Black Reef) (Wilson & Anhaeusser, 1998). Only mines in the Witwatersrand Basin are included in the study because the nature of the ore bodies is narrow and tabular. Although there are active mines in the East Rand, South Rand and Evander goldfields, these have been excluded from the study due to the lack of relevant data available in the public domain. Target (Free State) and South Deeps (West Rand) are also excluded because they follow a massive mechanical mining method. A geological cut-off approach is followed in these mines, as they are not suited to a more selective mining method where individual blocks could be extracted.

6.3 West Rand Goldfield

The West Rand Goldfield lies 25 km to the west of Johannesburg and extends from Krugersdorp in the north to Westonaria to the south (Robb & Robb, 1998) and is shown in Figure 6-1. Mining commenced in the West Rand Goldfield (1887) shortly after discovering the Central Rand Goldfield to the east (1886). Four principle mines were established from the amalgamation of the early mining operations: East Champ D'Or, Luipardsvlei Estates, West Rand Consolidated and Randfontein Estates (Robb & Robb, 1998).

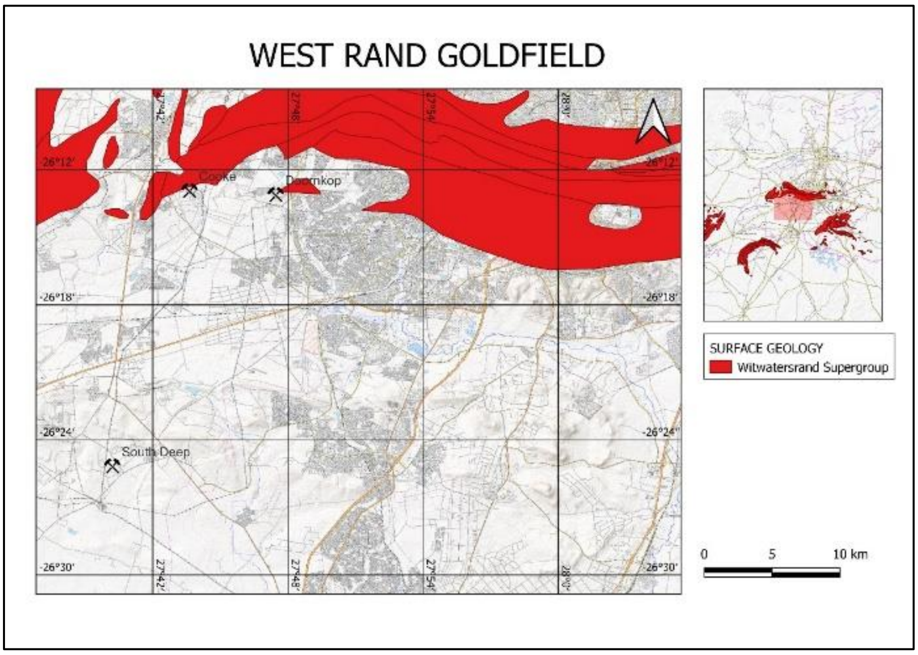

Figure 6-1. West Rand Goldfield (Council for Geoscience, 2021).

The current Doornkop Mine is on the site where the South Roodepoort Mine was initially established and formed part of Randfontein Estates (Robb & Robb, 1998). The Cooke Section of Randfontein Estates was developed in the 1970s. The Panvlakte Horst marks the western limit of the West Rand Goldfield (Robb & Robb, 1998) and separates it from the Venterspost and Lebanon mines of the West Wits. For the study, Doornkop and Cooke mines from this goldfield were considered.

The Central Rand Group (CRG) and the West Rand Group of the Witwatersrand Supergroup are exposed on the surface in the northern part of the West Rand Goldfield. The Transvaal and Ventersdorp sequences cover the Witwatersrand sequences at the Cooke and Doornkop mines.

The Johannesburg and Turffontein Subgroups represent the CRG. There are numerous economic horizons (over 20) within the CRG exploited for gold, uranium or both (Robb & Robb, 1998). Cooke Gold Mine exploited the

Composite Reef (E9 and UE1) in the Westonaria Formation of the Turffontein Subgroup (Robb & Robb, 1998). This mine is now under care and maintenance, reworking old dumps (Sibanye-Stillwater, 2020). No underground resources are declared for this mine, so further analysis will be excluded.

Doornkop Mine exploited the Kimberley Reefs (Robinson Formation of the Turffontein Subgroup), but this was suspended in 2014 to focus on the South Reef (Main Conglomerate Formation of the Johannesburg Subgroup). Mining of the Kimberley Reef may resume in the future (Harmony, 2021a). Doornkop has declared Mineral Reserves for the South, Main and Kimberley Reefs (Harmony, 2021a).

South Deeps Mine (now Gold Fields) is an extension of the old Westonaria Gold Mine. This mine exploits the Composite Reef equivalent of the Westonaria Formation and the 'Massives' (Robb & Robb, 1998). This economic horizon is up to 30 m thick and includes conglomerates of the Elsburg Formation (of the Turffontein Subgroup) and the Ventersdorp Contact Reef (VCR) of the Venterspost Formation (the base of the Westonaria Group of the Ventersdorp Supergroup) (Reddy & Germs, 1994; Robb & Robb, 1998). The 'Massives' are mined using massive mining methods and are thus excluded from the cut-off grade analysis.

6.3.1 Doornkop Mine

Doornkop Mine is a 2,000m deep single-shaft operation. It was developed by Johannesburg Consolidated Investments (JCI) during the 1980s. The initial production was focused on the shallower Kimberly Reef, with the deeper South Reef being targeted from the mid-1990s (Harmony, 2021a). Doornkop has published resources for the South Reef, Main Reef and Kimberly Reef. However, the mine only plans to produce gold from the South Reef. The Mineral Resource was estimated using 30 m x 30 m blocks for the Measured and 60 m x 60 m blocks for the Indicated Resources. These block sizes have been used when simulating the block list for this study (Harmony 2021). The published grade-tonnage curve reflects only the South Reef. The Mineral Resources are shown in Table 6-I.

Table 6-I. Doornkop Mine Mineral Resources (Harmony, 2021a).

	Measured				Indicated			
	Mt.	g/t	000kg	000oz	Mt.	g/t	000kg	000oz
South Reef	5.2	7.93	41.24	1,326	3.8	6.88	26.06	838

The annual milled tonnage is estimated to be 851,000 tonnes. The SW used is 124 cm. The percentage stope to milled tonnes and MRF are assumed to be 82% and 76%, respectively, based on the mine's annual Resources and Reserves report (Harmony 2021). The AISC used for the study (also obtained from the Harmony annual Resource and Reserve report is US$191/t (including royalty costs) and an estimated US$183/t (excluding royalty costs).

6.4 West Wits Goldfield

The area to the west of the West Rand goldfield was extensively explored during the 1930s. Dr Rudolf Krahmann identified that the magnetic shales within the Witwatersrand Basin could be traced under the younger sediments and lavas using a magnetometer. Gold Fields' chief mining engineer, Guy Carleton Jones, commissioned him, and the eastern portion of the West Wits line was discovered (London Bullion Market Association, 2022). The West Wits goldfield is separated into two portions by the Bank Fault. Kloof Consolidated (previously Kloof, Leeudorn, Venterspost and Libanon) are to the east, whilst Driefontein Consolidated (previously East and West Driefontein), Mponeng (previously Western Deep Levels), Kusasalethu (previously Deelkraal and Elandsrand), Blyvooruitzicht and Doornfontein are to the west (Robb & Robb, 1998).

The economically important horizons in the West Wits are the Carbon Leader Reef (west of the Bank Fault) and the Middlevlei Reef (east of the Bank Fault). These are found in the lower Randfontein Formation of the Johannesburg Subgroup of the CRG (Robb and Robb, 1998). The VCR has been extensively mined in the West Wits (Robb and Robb, 1998) and is currently the primary reef on many active shafts in this goldfield (Harmony, 2021; Sibanye-Stillwater, 2020).

The active mines included in the study are shown in Figure 6-2.

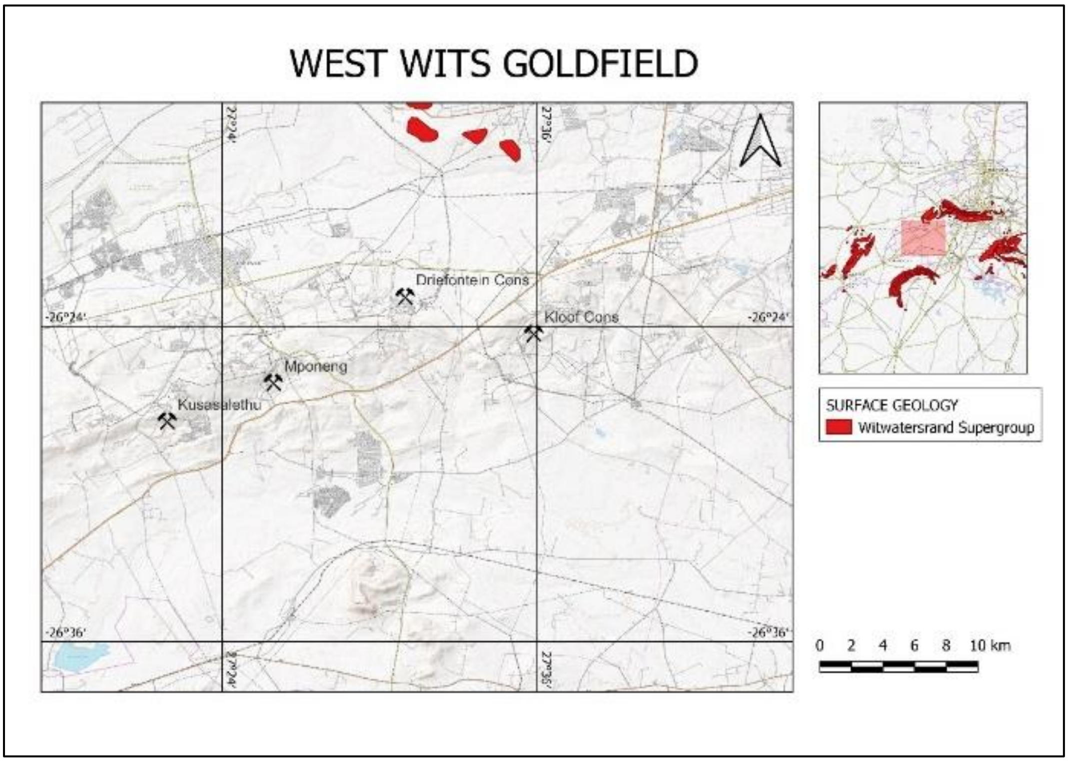

Figure 6-2. West Wits Goldfield (Council for Geoscience, 2021).

6.4.1 Driefontein Consolidated Mines

Gold Fields established West Driefontein in the 1940s, followed by East Driefontein in the late 1960s. The two mines merged in 1981 to form Driefontein Consolidated (Gold Fields, 2011). The mine currently has five operating shafts, which are as follows:

- 1 Shaft (Masakhane);

- 2 Shaft (Pitseng), which is hoisting ore from the 4 and 5 Shaft Mineral Resources;
- 4 Shaft (Ya Rona);
- 5 Shaft (Hlanganani); and
- 8 Shaft (Khomanane).

There is a single operational plant on the mine. The primary reef being exploited in the mine is the Multiband Carbon Leader Reef. Expansion into the VCR on 1 and 5 Shafts is expected to extend the life of the mine (Sibanye-Stillwater, 2020). Sibanye-Stillwater does not state the resource block sizes used for the Mineral Resource and Reserve estimations, which were used to create the simulated block list. The current Mineral Resources are shown in Table 6-II.

Table 6-II. Driefontein Consolidated Mineral Resources (Sibanye-Stillwater, 2020).

	Measured				Indicated			
	Mt.	g/t	000kg	000oz	Mt.	g/t	000kg	000oz
1 Shaft	4.5	11.9	53.18	1,710	4.0	11.1	44.60	1,434
4 Shaft	2.4	21.6	51.07	1,642	0.7	20.9	14.43	464
5 Shaft	3.7	9.7	35.73	1,149	3.8	11.6	43.88	1,411
8 Shaft	10.1	7.9	80.21	2,579	5.6	4.7	26.12	840

The grade-tonnage curve and the production and cost data are presented for the combined Driefontein Consolidated shafts. Ideally, the analysis would be run on each shaft separately. However, this is impossible without the specific grade-tonnage and costing information for each of the Driefontein shafts. The production costs and grades vary between the shafts (the same as what was found for Beatrix and Driefontein Consolidated).

Annual production of 1,474,000 milled tonnes was used for the analysis. This is comprised of the following sources:

- 1 Shaft – 300,000 t/a;

- 2 Shaft – 732,000 t/a;
- 4 Shaft – 300,000 t/a;
- 5 Shaft – 456,000 t/a; and
- 8 Shaft – 336,000 t/a (Sibanye-Stillwater, 2022a).

The MRF for Driefontein Consolidated is 82%, and the ratio of stope to milled tonnes is 81%, based on figures obtained from the annual Mineral Resources and Reserve report (Sibanye-Stillwater, 2022a). From the same report, the average SW is 152 cm with an AISC of US$337/t. The estimated royalty cost is US$23/t.

6.4.2 Kloof Consolidated Mines

Kloof Consolidated is comprised of shafts that previously belonged to the Venterspost, Libanon, Kloof and Leeudoorn Gold Mines (Gold Fields, 2011). Mining in the area commenced prior to the Second World War at the relatively shallow Venterspost Mine (deepest depth 2,300 m). The development of the Libanon Mine took place soon after the war. Mining at Kloof Mine commenced in 1963 with the sinking of the Main Shaft and its two sub-vertical shafts (1 Shaft and 2 Shaft)(Gold Fields, 2011). The development of Kloof 3 Shaft took place in the 1970s and Kloof 4 Shaft in the 1980s. Leeudoorn Mine was developed at the same time as Kloof 4 Shaft.

The deepest working level at Kloof Mine is 45 Level which is 3,347 m below the surface, although the reef in the lease area extends down to a depth of 3,700m (Gold Fields, 2011).

There are currently five operational shafts and two gold plants on the property. The operational shafts are Thuthukani (1 Shaft), Hlalanathi (3 Shaft), Ikamva (4 Shaft), Manyano (7 Shaft, which was previously Leeudoorn Mine), and Masimthembe (8 Shaft, which was previously Libanon Mine) (Sibanye-Stillwater, 2020).

The VCR is the primarily exploited reef (71%), followed by Kloof Reef (18%), Middlelvlei Reef (9%), and the Libanon Reef (2%). The Measured and Indicated Mineral Resources for the operational shafts are presented in Table 6-III.

Table 6-III. Kloof Consolidated Mineral Resources (Sibanye-Stillwater, 2020).

	Measured				Indicated			
	Mt.	g/t	000kg	000oz	Mt.	g/t	000kg	000oz
1 Shaft	7.3	12.2	88.91	2,859	15.6	5.2	80.61	2,592
3 Shaft	5.5	13.9	77.13	2,480	8.2	5.9	49.04	1,577
4 Shaft	6.2	13.0	80.70	2,595	4.9	8.6	41.64	1,339
7 Shaft	4.4	12.2	53.34	1,715	2.0	8.2	16.58	533
8 Shaft	10.7	9.4	100.58	3,234	6.6	6.7	44.29	1,424

The grade-tonnage curve and the production and cost data are presented for the combined Kloof shafts. Ideally, the analysis would be run on each shaft separately. However, this has proved impractical without the specific grade-tonnage and costing information for each Kloof shaft because the production costs and grades are too varied between the shafts (the same as what was found for Beatrix and Driefontein Consolidated).

The estimated production rates for the five operating shafts are given in the annual Mineral Resources and Reserve Report (Sibanye-Stillwater, 2022a)and are as follows:

- 1 Shaft – 936,000 t/a;
- 3 Shaft – 0 t/a;
- 4 Shaft – 756,000 t/a;
- 7 Shaft – 108,000 t/a; and
- 8 Shaft – 300,000 t/a.

The cost used for the study is US$327/t (estimated from an AISC of US$341/t, including royalty costs). The SW used is 171 cm (Sibanye-Stillwater 2020). The ratio of stope to milled tonnes obtained from the SW along with the published survey discrepancy and waste tonnes to the mill is 80%. The MRF used for the study is 83% (Sibanye-Stillwater, 2022a).

6.4.3 Kusasalethu Mine

Kusasalethu mine was formerly the Gold Fields Deelkraal and AngloGold Ashanti Elandrand mines amalgamated and bought by Harmony in 2001. The Deelkraal Shaft is closed, and mining is taking place from the Elandsrand Shaft. The upper levels of the mine are closed, and mining is currently taking place below the 98 Level. The mine is 3,388m deep (Harmony, 2021a). The VCR is mined using the sequential grid mining method. The Mineral Resources were estimated utilising 30 m x 30 m and 60 m x 60 m for the Measured and Indicated blocks, respectively (Harmony, 2021a). The Mineral Resources are shown in Table 6-IV.

Table 6-IV.Kusasalethu Gold Mine Mineral Resources (Harmony, 2021a).

	Measured				Indicated			
	Mt.	g/t	000kg	000oz	Mt.	g/t	000kg	000oz
VCR	3.4	11.15	38.13	1,226	12.6	9.05	114.01	3,668

The annual production estimated for the analysis is 708,000 milled t/a. The stope-to-milled tonnes ratio is 83%, with an MRF of 82%. The SW is estimated to be 136 cm. The AISC, including the royalty costs, is US$272/t (Harmony, 2021a), and the costs excluding royalty are estimated to be US$263/t.

6.4.4 Mponeng Mine

Mponeng Mine (along with the Savuka (2 Shaft) and Tau Tona (3 Shaft) Mines) was established by Anglo American as the Western Deep Levels Mine in 1957. Mponeng Mine (1 Shaft) is the newest of the three mines sunk during the 1980s. It is the World’s deepest mine, with a depth of 3,841 m (Harmony, 2021a). The primary reef is the VCR, with limited mining of the Carbon Leader Reef. The sequential grid mining method is employed.

The resource estimation was undertaken using 30 m x 30 m blocks for the Measured, and 60 m x 60 m blocks for the Indicated Resources (Harmony, 2021a), so 900 m^2 and 3,600 m^2 blocks have been used for creating the simulated block listing. The published Mineral Resources are shown in Table 6-V.

Table 6-V. Mponeng Gold Mine Mineral Resources (Harmony, 2021a).

	Measured				Indicated			
	Mt.	g/t	000kg	000oz	Mt.	g/t	000kg	000oz
VCR	2.9	15.61	45.53	1,464	21.7	14.11	306.37	9,851

An MRF of 71% has been assumed for the study. The estimated annual production is 683,000 milled tonnes per annum with a stope to the milled ratio of 71% - determined from the published SW and milled width (MW) figures. The AISC, including royalty costs, is US$276, whilst excluding the royalty costs are estimated to be US$260 (Harmony, 2021a).

6.5 Klerksdorp Goldfield

The Klerksdorp goldfield is about 160 km southwest of Johannesburg and includes the towns of Klerksdorp, Orkney and Stillfontein. The initial discovery of gold in the goldfield occurred the same year as the discovery of gold in the Central Rand goldfield at Langlaagte in 1886 (Robb & Robb, 1998). These discoveries were in the Dominion Reef and the Witwatersrand West Rand Group that outcrop in the region and did not lead to long-term mining. Exploration work carried out in the late 1920s and 1930s led to the exploitation of shallow CRG and VCR reserves in the area. The Strathmore Reef was discovered in 1931, but it was only identified as economically significant when it was intersected in 1942 and named the Vaal Reef (in the Strathmore Formation of the Johannesburg Group). In the 1950s, this discovery led to the Vaal Reefs, Stillfontein, Buffelfontein, and Hartebeesfontein mines (Robb & Robb, 1998) by Anglo American, General

Mining and Anglovaal, respectively. These mines focused on the Vaal Reef for the bulk of the gold produced (Robb & Robb, 1998). Currently, mining is still taking place in the region at the Tau Lekoa and Kopanang mines (obtained by Village Main Reef from AngloGold Ashanti) and Moab Khotsong (obtained from AngloGold Ashanti by Harmony). Only Moab Khotsong's (which includes the Great Noligwa Shaft) data are available in the public domain and are included in the study (Figure 6-3).

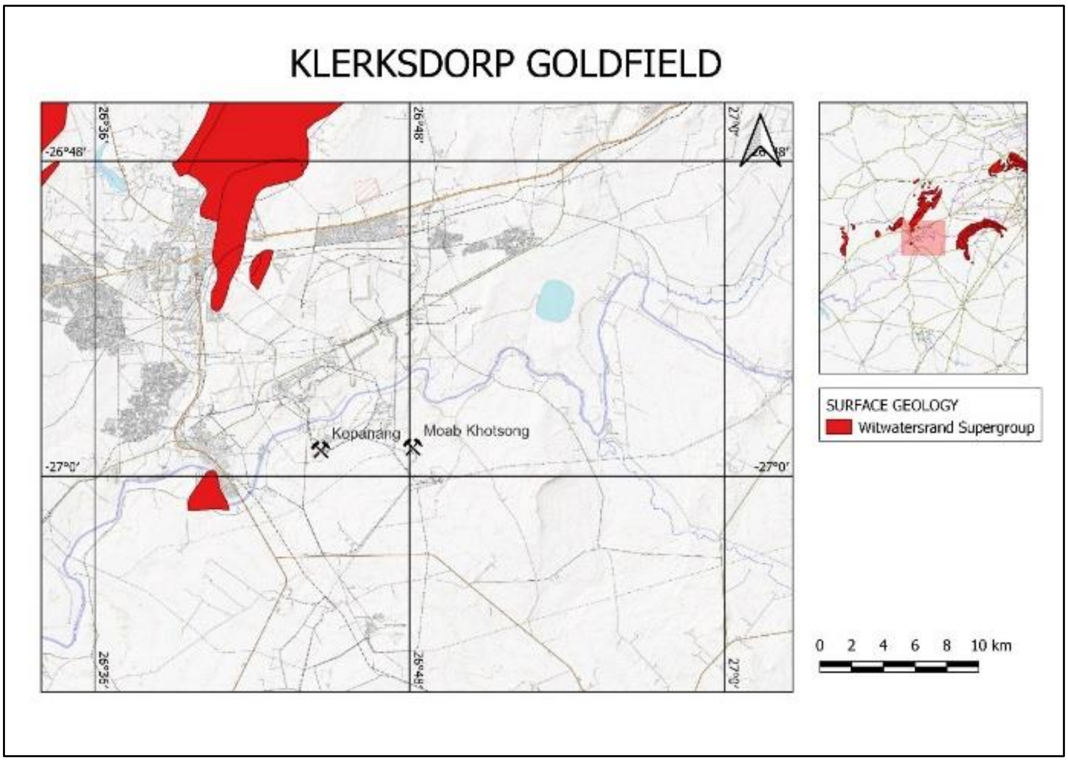

Figure 6-3. Klerksdorp Goldfield (Council for Geoscience, 2021).

6.5.1 Moab Khotsong Mine

The Harmony-owned Moab Khotsong Mine was bought from AngloGold Ashanti in 2018. It comprises the Moab Khotsong (production started in 2003) and Great Noligwa (1968) mines. The Vaal Reef is the foremost economic horizon on the mine and is exploited between 1,791 and 3,052 m below the surface (Harmony, 2021a). The Mineral Resources were estimated using 30 m x 30 m and 60 m x 60 m blocks for the Measured and

Indicated Resources, respectively. The published Mineral Resource is shown in Table 6-VI.

Table 6-VI. Moab Khotsong Gold Mine Mineral Resources (Harmony, 2021a).

	Measured				Indicated			
	Mt.	g/t	000kg	000oz	Mt.	g/t	000kg	000oz
Vaal Reef	4.2	16.75	70.72	2,274	14.0	15.95	222.52	7,155

The SW is estimated to be 177 cm, and the MW is 223 cm. These are used to estimate the stope-to-milled tonnage ratio of 79%. The estimated annual milled tonnes are 903,000 at an MRF of 73% (Harmony, 2021a). The annual Mineral Resource and Reserve report state an AISC of US$277/t. The costs, excluding the royalties, are estimated to be US$259/t.

6.6 Free State Goldfield

Mining in the Free State (or Welkom) goldfield commenced at General Mining's St Helena Gold Mine in 1945 (Robb & Robb, 1998). This was quickly followed by Anglovaal, Rand Mines and Anglo American mines developed in the region around Allanridge, Odendaalsrus and Virginia. In 1947, the town of Welkom was designed and constructed specifically to support the gold-mining community (Robb & Robb, 1998).

The primary economic horizon in the Free State goldfield is the CRG Basal Reef. This reef is subdivided into the Basal (to the north) and Steyn (in the south) placers (Robb & Robb, 1998). Besides the Basal Reef, other important economic horizons include the A-Reef, B-Reef, Leader Reef and Beatrix Reef (in the south at Joel and Beatrix Mines). North-south trending normal faulting has resulted in a series of horst and graben features that have dominated the mines' layout in this goldfield. This is due to the faulting influencing the depth of the Witwatersrand basin under the younger cover sequences (Robb & Robb, 1998).

The mines currently operating in the goldfield include Target, Tshepong (including Phakisa), Bambanani, Masimong, Beatrix and Joel (see Figure 6-4). Unisel Mine is not included in the study because it closed down in 2021 (Harmony, 2021a).

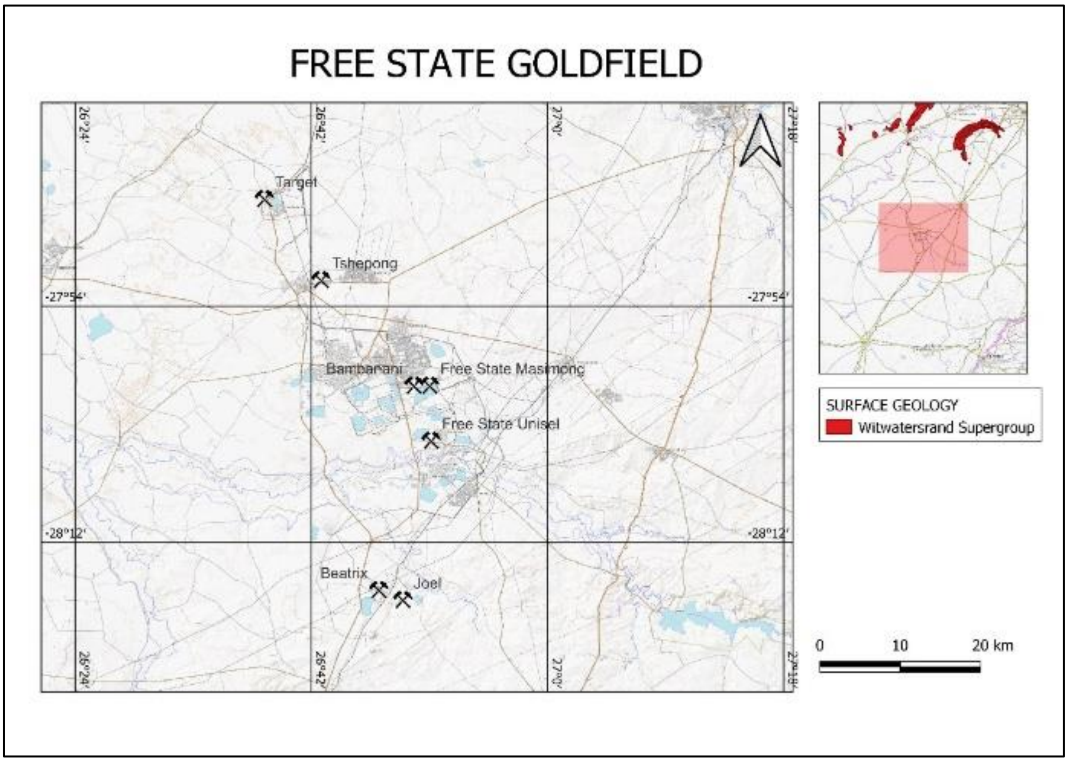

Figure 6-4. Free State Goldfield (Council for Geoscience, 2021).

At Target Mine, the orebody comprises 67 individual conglomerates (of the Uitkyk and Van der Heeversrust members of the upper Eldorado Formation). These are mined using massive mining techniques (Harmony, 2021a). This mine is excluded from the study due to the nature of the mining currently taking place in the operation (Harmony, 2021a).

6.6.1 Bambanani Mine

Anglo American Corporation sank President Steyn 4 Shaft to target the Basal Reef south of Welkom in the early 1970s. The sub-vertical shaft was sunk in the late 1970s to 3,328 m below the surface (the deepest mine in the Free State). When President Steyn Mine was closed in 1997, President Steyn 4 Shaft became known as Freegold 1 East and the older President Steyn 3 Shaft became Freegold 1 West. Subsequently, AngloGold changed the names to Bambanani East and West. Harmony bought the mines in 2003 (Harmony, 2021a).

The Basal Reef (Steyn Facies) is the predominant reef mined at Bambanani. The reef thickness is incredibly variable, from a few centimetres (carbon-rich seam) to many metres. Typically, the Basal Reef is 1-3 m thick (Harmony, 2021a). Although the Harmony Mineral Resource and Reserve states that 10 m x 10 m blocks are used for the mineral resource estimation, these would be considered too small to be mined as the SMU. This study has accepted these size blocks. Only Measured Resources are declared for Bambanani in the 2021 Mineral Resources and Mineral Reserve Report (Harmony, 2021a). These are shown in Table 6-VII.

Table 6-VII. Bambanani Mineral Resources (Harmony, 2021a).

	Measured				Indicated			
	Tonnes	g/t	000kg	000oz	Tonnes	g/t	000kg	000oz
Bambanani	0.4	13.48	5.63	181	-	-	-	-

Production on the mine is limited to the Babanani East Shaft pillar extraction. The ore is trammed underground and hoisted to the surface at the Bambanani West Shaft. The estimated production rate is 227,000 milled tonnes per annum (85% stope to milled tonnes) with an MRF of 82%. A SW of 210 cm, and the AISC is US$334 (including royalty costs), and an estimated US$324/t (excluding royalty costs) were used for the study (Harmony, 2021a)

6.6.2 Beatrix Mine

There are currently three shafts operating at Beatrix Mine. The 1 Shaft (South Section) and 3 Shaft (North Section) are predominantly mining the Elsburg VS5 and Aandenk Reefs. The 4 Shaft (West Section) was initially established as the Beisa Uranium Mine (targeting the Beisa Reef) and was closed in 1984 when the uranium prices collapsed (following the Chernobyl disaster) (Gold Fields, 2011). The mine was re-established as Oryx Gold Mine and targeted the Kalkoenkrans Composite Reef. Oryx Gold Mine merged with Beatrix Gold Mine in 2011. This mine is a significant distance from the Beatrix Gold Mine surface infrastructure, and there are no underground linkages between them. Oryx Gold Mine's layout was compromised because the Beisa Uranium Mine's shaft and underground infrastructure were adapted to target the gold-bearing Kalkoenkrans Composite Reef rather than the uranium-rich Beisa Reef. Sibanye Gold Limited (now Sibanye-Stillwater) was established in 2013 when the company was created through the unbundling of Gold Fields Limited, and Beatrix Gold Mine was included in the new entity (Sibanye-Stillwater, 2022b).

The reported Mineral Resources for Beatrix are split into three operations. These are shown in Table 6-VIII. The block sizes for the Measured and Indicated Resources are assumed to be different, with 900 m^2 for the Measured and 3,600 m^2 for the Indicated Resources. Sibanye-Stillwater does not specify the block sizes used in their annual Mineral Resource and Reserve Report, and so the same block size is assumed that Harmony uses for their Free State operations.

Table 6-VIII. Beatrix Mine Mineral Resources (Sibanye-Stillwater, 2020).

	Measured				Indicated			
	Mt	g/t	000kg	000oz	Mt	g/t	000kg	000oz
1 Shaft	3.1	7.2	22.33	718	3.3	5.5	18.26	587
3 Shaft	15.2	6.5	98.37	3,163	6.0	5.4	32.47	1,044
4 Shaft	2.9	11.5	33.56	1,079	4.6	8.4	38.60	1,241

The production rates for the three shafts are obtained from the annual Mineral Resources and Reserve Report, with the total being 1,826,000 t/a (Sibanye-Stillwater, 2022a). Ideally, the analysis would be run on each shaft separately. However, without the specific grade-tonnage and costing information for each of the Beatrix shafts, this is problematic because the production costs and grade profiles are too varied between the shafts (the same as what was found for Kloof and Driefontein Consolidated).

The AISC was obtained from the Sibanye-Stillwater annual 2021 Resources and Reserve Report and US$202/t (including royalty costs with US$195/t estimated if royalty costs are excluded). Considering the distance from the surface infrastructure and the compromised mine design, a higher AISC for 4 Shaft can be assumed. The low expected production rates at 1 Shaft would also lead to higher production costs.

The ratio of stope to milled tonnes obtained from the SW, along with the published survey discrepancy and waste tonnes to the mill, is 92%. The published MRF is 70%. The published grade tonnage curve in the annual Mineral Resources and Reserves Report was shown in cmg/t and could be converted directly to SW g/t without knowing the CW. An SW of 176 cm was used for the study (Sibanye-Stillwater, 2022a).

6.6.3 Joel Mine

JCI developed HJ Joel Mine in the mid-late 1980s. The name changed to Joel when AngloGold was established, and the JCI assets were split into

AngloGold and Anglo Platinum. Harmony acquired the mine from AngloGold in 2002 (Harmony, 2021a).

The mine has North and South sections. The North Shaft was sunk to 1,471 m below the surface but was never equipped to transport people. The South Shaft complex has twin shafts, and the depth is 1,050 m. The mine has a complex arrangement of chairlift declines and lift shafts to transport the employees from the shallow South Shaft to the deeper production areas in the North Shaft area. The plant was decommissioned in 2019, and the ore is processed at the Harmony One Plant in Welkom. The scattered mining method is practised at this intermediate-depth mine (Harmony, 2021a). Resource estimation of the Beatrix Reef has been conducted using 30 m x 30 m blocks for the Measured Resource and 60 m x 60 m for the Indicated Resource. As a result, 900 m^2 and 3,600 m^2 blocks have been utilised for the simulated block list created for this study. The Mineral Resources are tabulated in Table 6-IX.

Table 6-IX. Joel Gold Mine Mineral Resources (Harmony, 2021a).

	Measured				Indicated			
	Mt.	g/t	000kg	000oz	Mt.	g/t	000kg	000oz
Beatrix Reef	4.0	7.89	39.91	1,026	3.8	7.24	27.31	878

The cost used for the study is US$197/t (excluding royalty costs and estimated from the published AISC of US$205/t). A production rate of 359,000 t/a has been employed with a 92% ratio of stope to milled tonnes. The SW is 174 cm, and the MRF is 79% (Harmony, 2021a).

6.6.4 Masimong Mine

Erfdeel Mine was sunk by Anglo American in 1985 and had two shaft complexes. When Harmony purchased Saaiplaas 3 Shaft in 1997 and the Erfdeel Mine in 1998, the shafts were called Saaiplaas 3, 4 and 5. When Saaiplaas 3 Shaft closed, the Saaiplaas 4 and 5 shafts were renamed

Masimong 4 and 5 (Harmony, 2021a). Currently, only Masimong 5 Shaft is operational and mines predominantly Basal Reef (80%), with some Basal B Reef (20%). Mining takes place between 1,650 and 2,010 m below the surface. The ore is transported by rail to the Harmony One Plant in Welkom for processing (Harmony, 2021a). The Mineral Resources have been estimated using 30 m x 30 m blocks for the Measured Resource and 60 m x 60 m blocks for the Indicated Resource (Harmony 2021). The Mineral Resources are tabulated in Table 6-X.

Table 6-X. Masimong Gold Mine Mineral Resources (Harmony, 2021a).

	Measured				Indicated			
	Mt.	g/t	000kg	000oz	Mt.	g/t	000kg	000oz
Basal Reef	2.5	8.98	22.01	710	0.2	7.35	1.31	42

The annual production used for the analysis is 510,000 tonnes. The AISC is US$183/t (including royalties and US$178/t excluding royalties). The SW is 142 cm with a stope-to-milled tonne ratio of 91%. The MRF is 54% (Harmony, 2021a).

6.6.5 Tshepong Mine

Tshepong Mine shaft sinking was completed in 1991. Phakisa Mine shaft sinking commenced in 1994, but the mine was mothballed in 1999. Harmony acquired Tshepong and Phakisa from AngloGold in 2003 and completed the sinking of Phakisa in 2006. The depth of Phakisa is 2,427 m, while Tshepong is 2,161 m. Phakisa and Tshepong were integrated in 2017 as the Tshepong Operations. Nyala Shaft is also included in the integrated Tshepong Operations (Harmony, 2021a).

The Basal Reef is the primary gold-bearing horizon on the Tshepong Operations. Generally, on the Tshepong Mine, the shales above the conglomerate and quarzitic package are undercut. On Phakisa Mine, open stoping predominates in the southern areas whilst undercutting takes place in the north (Harmony, 2021a).

The Mineral Resources are evaluated using 30 m x 30 m and 60 m x 60 m blocks for the Measured and Indicated Resources, respectively. These are presented in Table 6-XI (Harmony, 2021a).

Table 6-XI. Tshepong Gold Mine Mineral Resources (Harmony, 2021a).

	Measured				Indicated			
	Mt.	g/t	000kg	000oz	Mt.	g/t	000kg	000oz
Basal Reef	24.9	11.47	285.96	9,195	12.3	10.61	130.34	4,191

Harmony reports an average SW for the mine of 113 cm with a milling width of 137 cm. This is used to determine a stope-to-milled tonne ratio of 83%. The MRF is 69%. The AISC (including royalties) is US$205/t and is estimated to be US$192/t (excluding royalty costs) (Harmony, 2021a).

6.7 Cost and Production Data Summary

The cost and production figures are summarised for the mines in Table 6-X11. These are obtained from the companies' annual Mineral Resource and Reserve reports. Although every effort has been made to obtain accurate data, the research aims to compare the effects of the mineral royalty costs on the optimised cut-off grades rather than give definitive profit/NPV estimates.

Table 6-XII. Mine production and cost estimates (Harmony, 2021a; Sibanye-Stillwater, 2022a).

Mine	Planned Milled Tonnes (Mt)	Stope to Milled Tonnes	SW (cm)	MRF	AISC (US$/t) Including Royalty	Cost (SU$/t) Excluding Royalty
West Rand Goldfield						
Doornkop	851,000	81.6%	124	75.8%	US$191	US$183
West Wits Goldfield						
Driefontein	1,474,000	80.9%	152	82.4%	US$337	US$314
Kloof	1,862,000	80.3%	171	83.3%	US$341	US$327
Kusasalethu	708,000	82.4%	136	81.7%	US$272	US$263
Mponeng	683,000	70.7%	152	79.4%	US$276	US$260
Klerksdorp Goldfield						
Moab Khotsong	903,000	79.4%	177	72.8%	US$277	US$259
Free State Goldfield						
Bambababi	227,000	85.4%	210	81.6%	US$334	US$324
Beatrix	1,826,000	91.7%	176	69.6%	US$202	US$195
Joel	359,000	91.6%	174	78.9%	US$205	US$197
Masimong	510,000	91.0%	142	54.2%	US$183	US$178
Tshepong	1,558,000	82.5%	113	69.4%	US$205	US$192

6.8 Chapter Summary

This chapter has introduced the four gold mining areas where mines included in the study are located, the ore bodies are introduced, and the mines' financial and production estimates for the study are determined. The Measured and Indicated Resources are tabulated for each of the mines. The AISC and production estimates are obtained from the 2021 Mineral Resource and Reserve reports for the companies.

Only gold mines are included in the study. The public reporting of the platinum mines following conventional mining methods was reviewed and found to exclude grade-tonnage curves. These curves are required to simulate the block listings that are the starting point for the BirchOptimiser created for this study. Furthermore, the platinum mines reviewed do not include SW, PCF, and the ratio of stope to milled tonnes, which is essential to determine the cut-off grades (Maseko, 2018). It was noted that the platinum mines do not employ cut-off grades when conducting mine planning to identify payable blocks but rather geological cut-offs and pay limits for the entire operation.

The following chapter will use the data in the model developed in the thesis to determine which approach is best when calculating cut-off grades considering the mineral resource royalty costs.

7 THE MINERAL RESOURCE ROYALTY CUT-OFF GRADE OPTIMISATION STUDY

7.1 Introduction

This section presents the analysis of the impact of the mineral resource royalty on the cut-off grade and resultant profit and $NPV_{12\%}$ values for each of the mines selected for the study.

The base case for the study is considered the break-even grade, including the estimated cost for the mineral resource royalty, which is then applied as the cut-off grade. This assumption is based on the initial study's findings (Birch, 2016a) that established the standard industry practice. The break-even grade, excluding mineral resource royalty costs, is also established. For these two approaches, the profit, NPV, total tonnes mined and AMG are determined for comparison to the various financial optimised values obtained using the following approaches:

- Setting the royalty costs to US$0;
- Setting the royalty costs to be 0.5% of the total revenue;
- Using the royalty cost (US$/tonne), which was determined by the previous production year;
- Estimating the royalty rate based on the forecast production and the resultant profitability ratio; or
- Assume that the highest rate will be applied (5% because all the gold mines included in the study apply the refined mineral resource royalty rate).

For each of these approaches, the BirchOptimiser is used to determine the cut-off grade. These cut-off grades are then inserted into the cash flow to determine the resultant stope tonnes above the cut-off grade and the resultant milled tonnes, AMG, profit and NPV. The BirchOptimiser is then run, allowing the mineral resource royalty rate to be variable, and the model automatically determines the optimal cut-off grade. This cut-off grade is compared to the cut-off grades (along with the resultant profit) for each of the listed approaches to determine the optimal approach to estimating the mineral resource costs when establishing the cut-off grade. Finally, the BirchOptimiser optimises the $NPV_{12\%}$ rather than the profit.

2022 is considered the first production year. The 2021 gold price for this study is assumed to be US$1799/oz (Statista, 2022).

Block listings have been created for the analysis based on the published Mineral Resources and Reserves. The process followed to convert the grade-tonnage curves back into blocks by plotting the tonnages in the different grade categories.

The grade-tonnage curves published in the annual Mineral Resource and Reserve reports are measured at either 1 g/t or 100 cmg/t intervals. These measurements are converted into probabilities the then evaluated using the @Risk distribution fitting function.

The tonnage for the blocks to be populated (split into Measured and Inferred) is determined by the block sizes indicated in the reports, stoping width, and the density.

Once the tonnage for each block is determined, the total number of blocks required to add up to the published Measured and Indicated Resources can be determined. The best @Risk distribution function is then used to fill each block with a grade. The average grade is adjusted to match the published Resource grade.

The g/t blocks are then adjusted from g/t over the channel width to g/t over the stoping width.

The distribution of the grades is determined using the Fit function in Palisade @Risk software. The block sizes are accepted from the companies' mineral resource and reserve reports, and the number of blocks is based on the published Measured and Indicated Resource tonnage and CW data.

This data may not match the mine data precisely, considering that the mines' block listing has different sizes for each block. For this study, which determines the effect of the mineral resource royalties, they are considered acceptable, considering the block listings are not released into the public domain. The total Mineral Resources are used when mines have split their Mineral Resources between the different operations (for example, Kloof and Driefontein Consolidated). Unfortunately, the published grade-tonnage curves in the Annual Resource and Reserve Reports do not reflect the individual operations (or the individual ore bodies being mined). The published AISC data are also for the combined operation. If the mining companies carried out similar optimisation exercises, each operation would be treated separately using the block listings and costing information that is available to them.

This chapter identifies the optimal approach that mines should consider when considering the mineral resource royalty cost in their cut-off grade estimations. This approach is then compared to the base case for each of the mines included in the study. This is to identify the differences achievable by adopting the approach.

7.2 Identifying the Optimal Approach

The break-even grade with an estimated royalty rate is considered the base case. This is due to the findings in the initial research exercise, which indicated that this is the approach followed by the mines investigated (Birch, 2016a).

The break-even grade, for example, Kusasalethu Mine, would be calculated as follows using the break-even grade formula (modified from Equation 5 and Equation 11):

Cost US$/t excl. Royalties	$262.73
Royalties (US$/t)	$9.66
All-in Sustaining Costs (US$/t)	$272.39
Gold Price (US$)	$1,799
Planned tonnes per annum	708,000
MRF	81.7%
Ratio Stope/Milled tonnes	82.4%

Cost US$/t incl Royalties ÷ ((Gold Price (US$) ÷ 31.1) ÷ (MRF x Ratio Stope/Milled tonnes)

272.39 ÷ (1,799 ÷ 31.1) ÷ (0.817 x 0.824)

= 6.99 g/t

This value can be compared to the break-even grade, where no costs for the royalty are considered. For Kusasalethu Mine, this would be:

Cost US$/t excl. Royalties	$262.73
Gold Price (US$)	$1,799
Planned tonnes per annum	708,000
MRF	81.7%
Ratio Stope/Milled tonnes	82.4%

Cost US$/t excl. Royalties ÷ ((Gold Price (US$) ÷ 31.1) ÷ (MRF x Ratio Stope/Milled tonnes)

262.73 ÷ (1,799 ÷ 31.1) ÷ (0.817 x 0.824)

= 6.75 g/t

This is followed by comparing the optimised cut-off grade where the royalty rate is set to 0%, 0.5%, the royalty cost for the previous year (2.40%), and the estimated rate for the current year (2.79%) and 5.0%. For Kusasalethu Mine, the BirchOptimiser determined cut-off grades of 6.58, 6.58, 6.73, 6.76 and 6.91 g/t for each scenario.

The difference between the cut-off grades determined by the break-even approach (with no royalty costs) and those obtained from the BirchOptimiser (with 0% royalty cost) demonstrate the effect of the BirchOptimiser considering the lower profitability in the calculation. This reduces the total cost of the royalty as well as the income tax (determined using the gold tax formula). A 2.5% difference (0.17 g/t) was noted between these two cut-off grades for this Kusasalethu example.

The BirchOptimiser is then allowed to optimise the cut-off grade where the model selects its mineral resource royalty rate (the variable rate approach). The cut-off grade obtained using this approach is 6.60 g/t. This approach also gives the highest profit in all cases. The difference in the base-case cut-off grade (using the AISC that includes the estimated royalty costs) and variable rate profit-optimised cut-off grade using the BirchOptimiser was noted to be 0.39 g/t (a difference of 5.6%).

Finally, the BirchOptimiser is set to optimise the $NPV_{12\%}$, and the cut-off grade was calculated at 8.39 g/t for Kusasalethu Mine.

The figures for Kusasalethu Mine are presented as an example for the explanation of the BirchOptimiser in Appendix 1. For all the mines included in the study, tables with the break-even and cut-off grades, stope tonnes above cut-off grade, AMG, profit and $NPV_{12\%}$ for the different approaches are presented in Appendix 2 (A2.1 – A2.11). These tables show how these parameters differ in comparison to the base case break-even approach for each of the different approaches.

Due to the slightly higher profit obtained by the profit optimiser (with variable royalty rate) in all cases reviewed, this approach was selected as the most favourable. Red values indicate the highest profit obtained in each case in the profit tables in Appendix 2 (A2.1 – A2.11). This approach is very flexible and allows for the later aspects investigated in this study (multiple-criteria cut-off grade optimisation and proposed changes to income taxes). Setting the royalty costs to 0% or 0,5% in the BirchOptimiser also results in very similar cut-off grades (and in some cases, the same cut-off grade). The break-even base case and the profit-optimised (using the variable royalty rate) model will be compared for the detailed analysis of the mines included in the study.

7.3 Mine Analysis

The following grade-tonnage curves for each mine investigated are used to demonstrate the difference between the base case break-even grade and the profit-optimised cut-off grade (with variable royalty rate) obtained using the BirchOptimiser.

7.3.1 West Rand Goldfield

Doornkop Mine

Table 7-I shows the results of the cut-off grade optimisation analysis for Doornkop Mine.

Table 7-I. Break-even base-case versus profit-optimised (variable royalty rate) for Doornkop Mine.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	5.33	5.00	-6.1%
Total Stope Tonnes	Mt	5.35	6.04	12.9%
Total Milled Tonnes	Mt	6.56	7.40	12.9%
LoM	years	8	9	12.5%
AMG	g/t	7.47	7.20	-3.5%
Profit	US$ m	$358.72	$361.68	0.8%
NPV	US$ m	$225.72	$217.02	-3.9%
Total Revenue	US$ m	$1,751.60	$1,907.82	8.9%
Total Mining Costs	US$ m	($1,200.35)	($1,355.21)	12.9%
Total Royalties	US$ m	($52.86)	($53.75)	1.7%
Total Income Tax (gold tax)	US$ m	($139.68)	($137.18)	-1.8%
Total Tax Contribution	US$ m	($387.00)	($405.25)	4.7%

The base case break-even grade for Doornkop Mine is estimated to be 5.33 g/t, which results in an AMG of 7.47 g/t. The stope tonnes above break-even grade are estimated to be 5.35 million. The profit-optimised (variable royalty rate) cut-off grade drops to 5.00 g/t with an AMG of 7.20 g/t. The tonnes above the cut-off grade are estimated to be 6.04 million (an increase of 12.9%. There is a slight increase in profit (0.8%). The combined mineral resource royalty and income tax costs dropped by 0.8%. The profit-optimised approach with the variable resource royalty results in 8.9% more revenue, whilst the overall costs increase by 12.9%.

The grade-tonnage curve for Doornkop Mine is presented in Figure 7-1, showing the differences between the two approaches (cut-off grade, stope tonnage above cut-off grade and AMG).

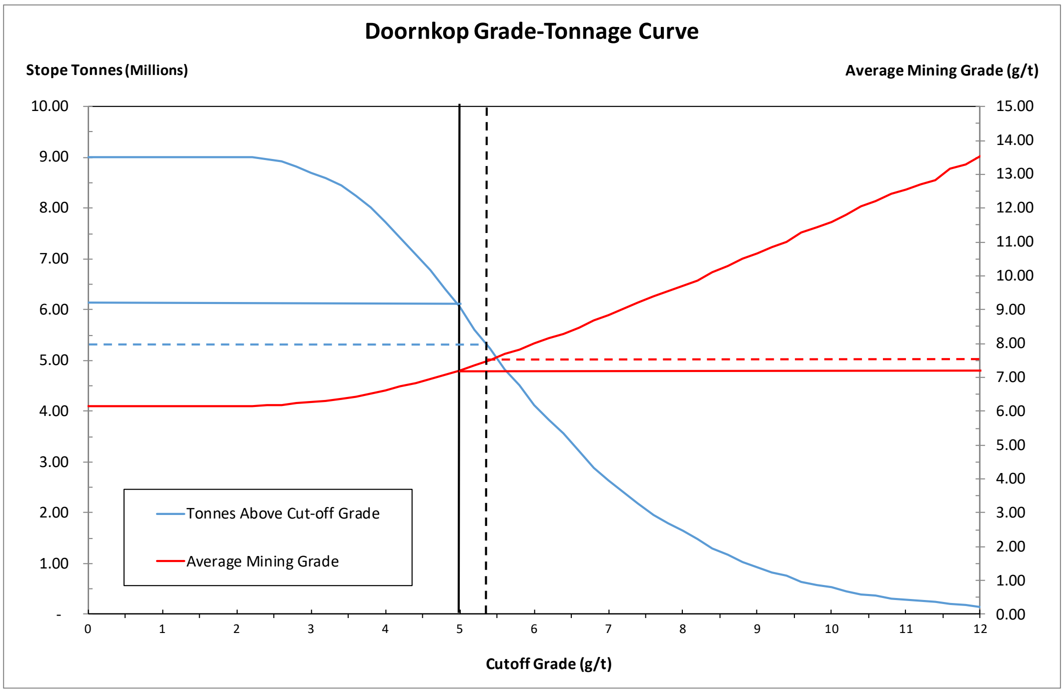

Figure 7-1. Doornkop Mine grade-tonnage curve. Dashed lines represent the break-even approach, while solid lines represent the profit-optimised cut-off grade approach.

There is a 3.5% drop in the profit-optimised (variable royalty rate) cut-off grade determined by the BirchOptimiser compared to the base case break-even grade calculated with an estimated royalty cost. This results in an increase of 13% stope tonnes above the cut-off grade. The increase in profit is only 0.8%, not considering the expected reduced development costs because more of the available blocks will be mineable. Table 7-II shows the difference in mineral resource royalty and income tax (gold tax) rates considering the two approaches. The complete analysis is presented in Appendix A2.1.

Table 7-II. Doornkop Mine royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	3.02%	28.03%
Profit-optimised (variable royalty rate) cut-off grade	2.82%	27.50%

Using the cut-off grade determined by the BirchOptimiser (profit-optimised with variable royalty rate) results in the total revenue increasing by 8.9% (US$1,752 to US$1,908 million). The total mining costs incurred by the mine increased by 12.9% (US$1,200 to US$1,355 million). The mineral resource royalty payable to the State increases by 1.7% (US$52.86 to US$53.75 million), but the income tax (gold tax formula) decreases by 1.8% (US$139.7 to US$137.2 million). Overall, the State receives 0.8% less revenue in direct taxes but would significantly boost the total tax contribution (through taxes borne and employees' income taxes) considering the significant increase in the total revenue and mining costs (4.7%). The LoM increases by 12.5% (1 year extra).

7.3.2 West Wits Goldfield

Driefontein Consolidated Mines

The Driefontein Consolidated grade-tonnage curve is shown in Figure 7-2.

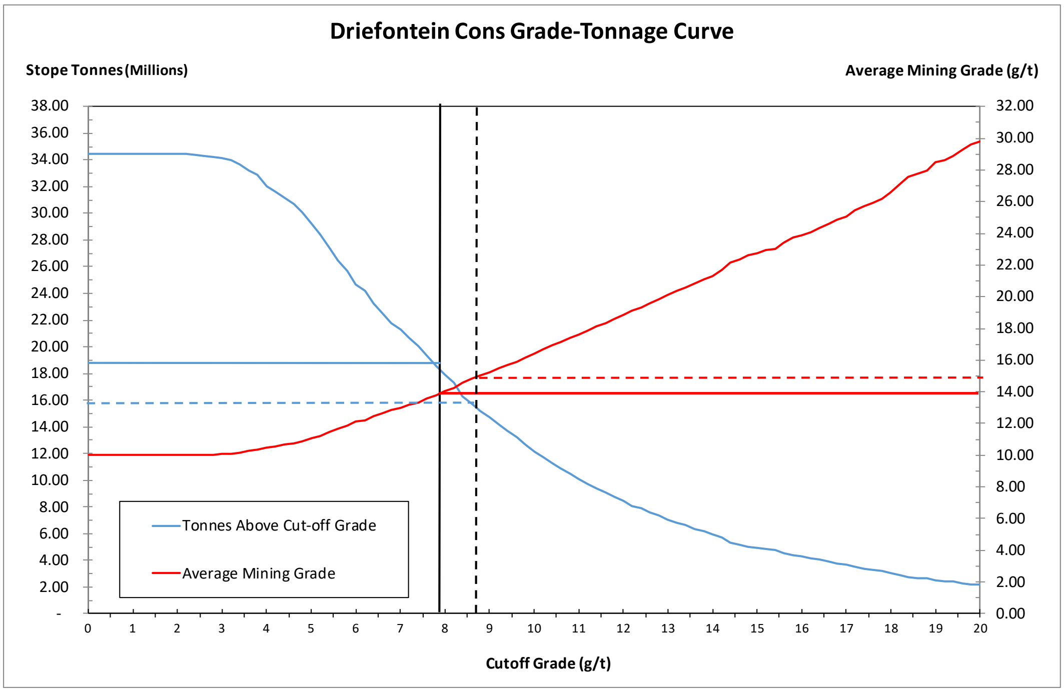

Figure 7-2. Driefontein Consolidated grade-tonnage curve. Dashed lines represent the break-even approach, while solid lines represent the profit-optimised cut-off grade approach.

It can be observed in Figure 7-2 that the base case break-even grade is 8.75 g/t whilst the profit-optimised (variable royalty rate) cut-off grade is 7.97 g/t (a drop of almost 9%). This drop results in AMGs of 14.98 and 13.97 g/t, respectively, a difference of 6.8%. There are 15.3 million stope tonnes above the base case break-even grade, whilst there are 18.1 million tonnes when the financial profit-optimised (variable royalty rate) cut-off grade is used. This is an 18.1% increase in mineable stope tonnes.

Table 7-III shows the results obtained from the cut-off grade optimisation analysis for Driefontein Cons Mine.

Table 7-III. Break-even base-case versus profit-optimised (variable royalty rate) for Driefontein Consolidated Mines.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	8.75	7.97	-8.91%
Total Stope Tonnes	Mt	15.30	18.07	18.11%
Total Milled Tonnes	Mt	18.93	22.35	18.11%
LoM	years	13	16	23.08%
AMG	g/t	14.98	13.97	-6.80%
Profit	US$ m	$3,175.11	$3,205.14	0.95%
NPV	US$ m	$1,579.36	$1,445.17	-8.50%
Total Revenue	US$ m	$10,929.49	$12,030.92	10.08%
Total Mining Costs	US$ m	($5,946.99)	($7,023.81)	18.11%
Total Royalties	US$ m	($453.25)	($460.72)	1.65%
Total Income Tax (gold tax)	US$ m	($1,354.14)	($1,341.24)	-0.95%
Total Tax Contribution	US$ m	($2,922.01)	($3,052.60)	4.47%

The calculated profit increases by 1% if the profit-optimised (variable royalty rate) is used. This difference in profit does not account for the increased utilisation of the ground opened up by the development and is considered understated. Appendix A2.2 presents the complete analysis.

Table 7-IV shows the difference in mineral resource royalty and income tax (gold tax) rates determined through the two approaches.

Table 7-IV. Driefontein Cons royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	4.15%	29.90%
Profit-optimised (variable royalty rate) cut-off grade	3.83%	28.50%

This table shows how lowering the cut-off grade results in lower income tax (gold tax) and royalty rates, even though the profit has increased. However, the mine will pay 1.7% more in mineral royalties (US$460.7 vs US$453.3 million). The income tax will drop by 1% (US$1,354 to US$1,341 million). Overall revenue from the mine will increase by 10.1% (US$10,929 to US$12,031 million), and total mining costs will increase by 18.1% (US$5,947 to US$7,024 million). This total revenue and mining cost increase would also significantly increase the total tax contribution to the state (4.5%).

Kloof Consolidated Mines

There is a 6% decrease in the profit-optimised (variable royalty rate) cut-off grade compared to the base case break-even grade on Kloof Consolidated (8.85 to 8.30 g/t). The drop results in a difference of 3.5% in the AMG (12.47 to 12.04 g/t) and a 12.5% increase in stoping tonnes above the cut-off grade (30.91 to 34.77 million tonnes). The grade-tonnage graph is presented in Figure 7-3.

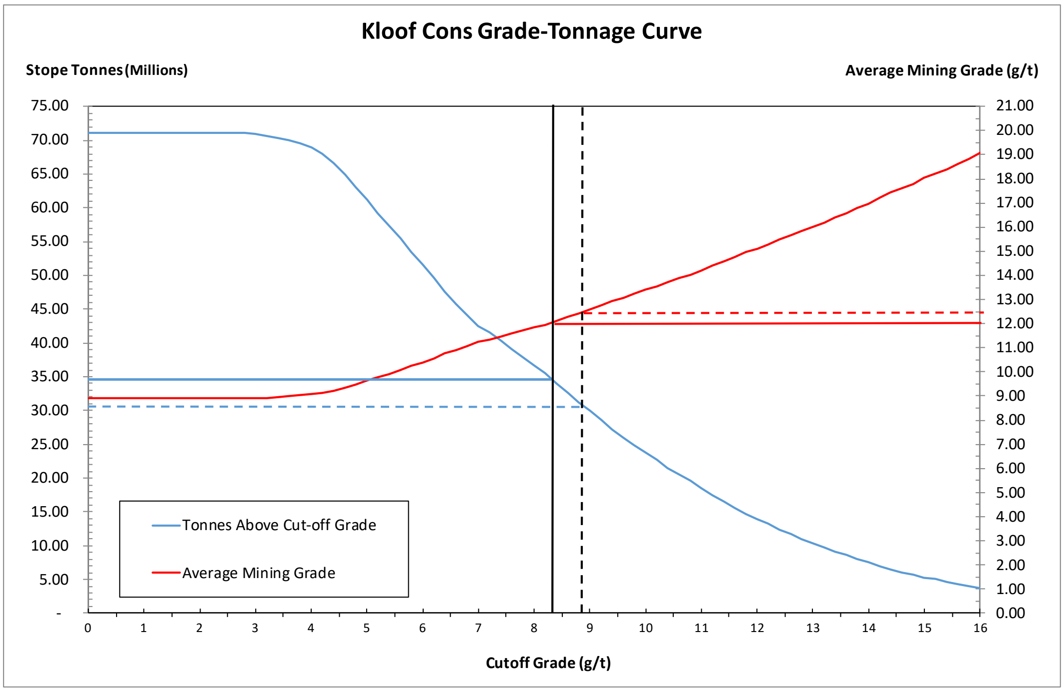

Figure 7-3. Kloof Consolidated grade-tonnage curve. Dashed lines represent the break-even approach, while solid lines represent the profit-optimised cut-off grade approach.

The profit increases by 0.8% from US$3,853 to US$3,883 million following the decrease in the cut-off grade. This does not consider the better utilisation of the ore body and subsequently lower development to stoping costs. Table 7-V shows how the royalty and gold tax rates drop even though the overall profit has increased.

Table 7-V. Kloof Cons royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	3.05%	28.11%
Profit-optimised (variable royalty rate) cut-off grade	2.86%	27.61%

Appendix A2.3 shows the results of the complete analysis.

There is an increase of 8.6% in the total revenue if the mine uses the profit-optimised (variable royalty rate) cut-off grade determined by the BirchOptimiser rather than the break-even grade, including royalty costs

(US$$18,571 to US$$20,167 million). The mining costs increase by 12.5% (US$12,644 to US$14,226 million). There is an overall drop in direct taxes of 0.8%. This drop comprises a 1.6% increase in royalty (US$567.0 to US$576.1 million) and a 0.6% decrease in income tax (US$2,074 to US$2,057 million). This decrease in direct revenue to the State is offset by the additional taxes borne and employees' income taxes due to the increased revenue and production costs (4.4%). Table 7-VI shows all the results comparing the two cut-off grade optimisation approaches.

Table 7-VI. Kloof Consolidated Mines comparison between break-even base case and profit-optimised (with variable royalty rate) exercise.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	8.85	8.30	-6.21%
Total Stope Tonnes	Mt	30.91	34.80	12.58%
Total Milled Tonnes	Mt	38.50	43.34	12.58%
LoM	years	21	24	14.29%
AMG	g/t	12.47	12.03	-3.50%
Profit	US$ m	$3,853.15	$3,883.37	0.78%
NPV	US$ m	$1,403.68	$1,290.74	-8.05%
Total Revenue	US$ m	$18,570.63	$20,174.93	8.64%
Total Mining Costs	US$ m	($12,643.86)	($14,234.60)	12.58%
Total Royalties	US$ m	($566.99)	($576.10)	1.61%
Total Income Tax (gold tax)	US$ m	($1,506.62)	($1,480.87)	-1.71%
Total Tax Contribution	US$ m	($4,050.18)	($4,226.48)	4.35%

Kusasalethu Mine

The profit-optimised (variable royalty rate) cut-off grade is 7.07 g/t. This is 5.3% lower than the break-even grade determined with the estimated mineral resource royalty costs included (7.47 g/t). Table 7-VII compares the cut-off grade optimisation exercise using the two approaches.

Table 7-VII. Kusasalethu Mine break-even cut-off grade vs profit-optimised (with variable resource rate) cut-off grade.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	6.99	6.60	-5.58%
Total Stope Tonnes	Mt	9.59	10.42	8.61%
Total Milled Tonnes	Mt	11.64	12.64	8.61%
LoM	years	17	18	5.88%
AMG	g/t	9.45	9.24	-2.24%
Profit	US$ m	$804.95	$809.56	0.57%
NPV	US$ m	$344.58	$327.83	-4.86%
Total Revenue	US$ m	$4,287.38	$4,552.18	6.18%
Total Mining Costs	US$ m	($3,058.43)	($3,321.62)	8.61%
Total Royalties	US$ m	($119.75)	($121.21)	1.21%
Total Income Tax (gold tax)	US$ m	($304.24)	($299.79)	-1.46%
Total Tax Contribution	US$ m	($897.21)	($927.56)	3.38%

The impact on the AMG and stope tonnes above the break-even (dashed lines) or cut-off grade (solid lines) are shown in Figure 7-4.

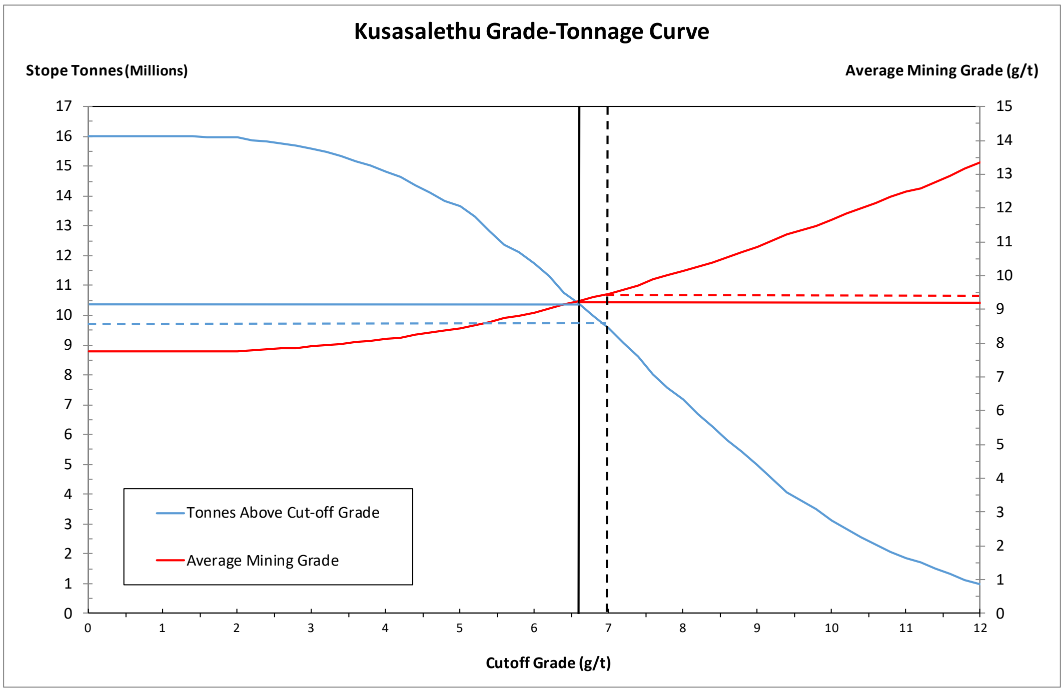

Figure 7-4. Kusasalethu Mine grade-tonnage curve.

The difference in stope tonnes above break-even/cut-off grade is 8.7% (9.6 to 10.4 million tonnes), and the AMG decreases by 2.3% (9.45 to 9.24 g/t) for the two approaches. There is an increase of 0.6% in profit (US$804.9 to US$809.6 million).

Table 7-VIII. Kusasalethu Mine royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	2.79%	27.43%
Profit-optimised (variable royalty rate) cut-off grade	2.66%	27.02%

Table 7-VIII shows how the mineral resource royalty and income tax rates alter as the cut-off grade lowers, resulting in lower rates despite increased overall profit. Appendix A2.4 presents the complete analysis.

Decreasing the cut-off grade as determined by the profit-optimised (variable royalty rate) approach increases the total revenue from Kusasalethu Mine from US$4,287 to US$4,556 million (an increase of 6.3%). The total mining costs increase 8.7%, from US$3,058 to US$3,326 million. Mineral resource royalties increase by 1.2% (US$119.8 to US$121.2 million) whilst income tax drops by 1.5% (US$304.2 to US$299.7 million). The State would receive 0.7% less direct tax revenue, but Kusasalethu's total tax contribution will increase (3.4%).

Mponeng Mine

Figure 7-5 shows the Mponeng Mine grade-tonnage curve.

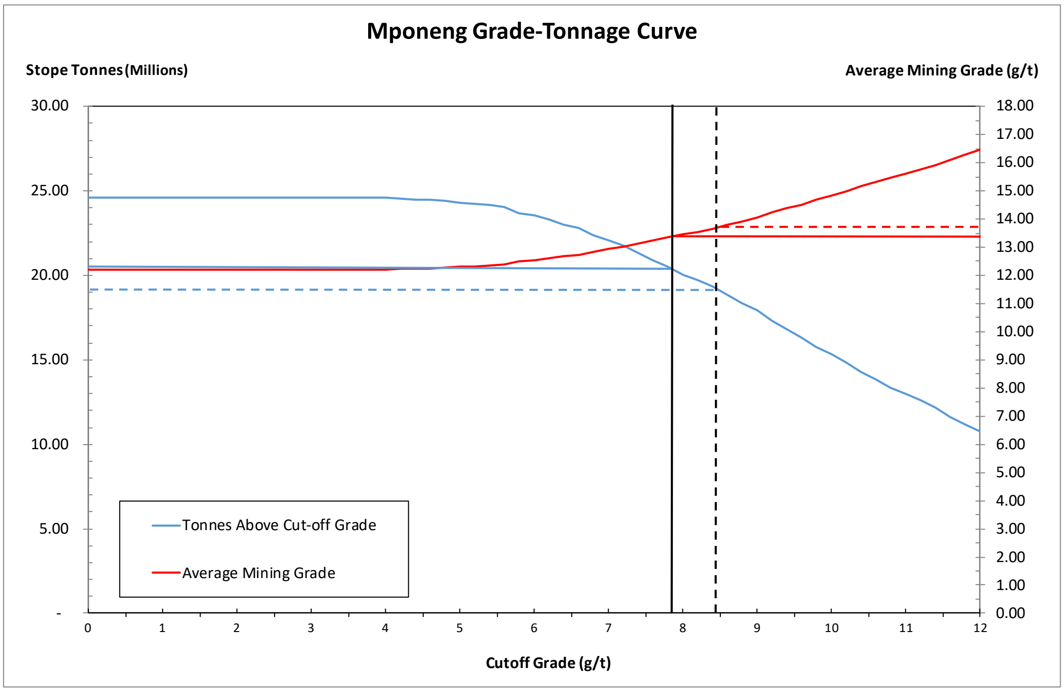

Figure 7-5. Mponeng Mine grade-tonnage curve. Dashed lines represent the break-even approach, while solid lines represent the profit-optimised cut-off grade approach.

It can be observed in Figure 7-5 that the break-even and profit-optimised (variable royalty rate) cut-off grades for the two approaches are 9.23 and 8.56 g/t, respectively. This 7.2% drop increases the stope tonnage above the break-even/cut-off grades by 9.9% (17.24 to 18.95 million tonnes). The AMG drops by 3.4% (14.25 to 13.77 g/t).

Table 7-IX shows the full comparison results between the two cut-off grade optimisation approaches.

Table 7-IX. Mponeng Mine cut-off optimisation exercise results.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	8.49	7.83	-7.77%
Total Stope Tonnes	Mt	19.12	20.45	6.97%
Total Milled Tonnes	Mt	27.05	28.93	6.97%
LoM	years	40	43	7.50%
AMG	g/t	13.72	13.36	-2.64%
Profit	US$ m	$3,213.41	$3,225.82	0.39%
NPV	US$ m	$668.61	$629.40	-5.86%
Total Revenue	US$ m	$12,048.95	$12,547.76	4.14%
Total Mining Costs	US$ m	($7,028.62)	($7,518.26)	6.97%
Total Royalties	US$ m	($461.87)	($465.10)	0.70%
Total Income Tax (gold tax)	US$ m	($1,345.04)	($1,338.58)	-0.48%
Total Tax Contribution	US$ m	($2,980.69)	($3,033.81)	1.78%

There is an increase in profit from US$3,213 to US$3,226 million (a 0.4% increase). Table 7-X shows how the mineral resource royalty and gold tax rates differ between the two approaches. The complete analysis is presented in Appendix A2.5.

Table 7-X. Mponeng Mine royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	3.83%	29.51%
Profit-optimised (variable royalty rate) cut-off grade	3.71%	29.33%

The lower royalty rate for the profit-optimised (variable royalty rate) cut-off grade approach shown in Table 7-X results in 0.7% higher revenue to the State (US$461.9 to US$465.1 million), considering it is applied to 4.2% higher revenue (US$12,049 to US$12,549 million). The income tax is 0.5% lower (US$1,345 to US$1,339 million), but this is offset by taxes borne and employees' income taxes (1.8%) due to the increase in total revenue and 7% increase in mining costs (US$7,029 to US$7,520 million).

7.3.3 Klerksdorp Goldfield

Moab Khotsong Mine

The profit-optimised (variable royalty rate) cut-off grade (11.74 g/t) for Moab Khotsong Mine is 4.8% lower than the break-even grade calculated, including royalty costs (12.34 g/t). Lowering the cut-off grade increases tonnes above the cut-off grade from 11.98 to 13.12 million tonnes (an increase of 9.5%). The AMG drops from 15.47 to 15.17 g/t (a 1.9% decrease). This is shown in Figure 7-6. The complete analysis of the various approaches for Moab Khotsong Mine can be found in Appendix A2.6, but the comparison between the base case break-even cut-off grade and profit-optimised (with variable royalty rate) is shown in Table 7-XI.

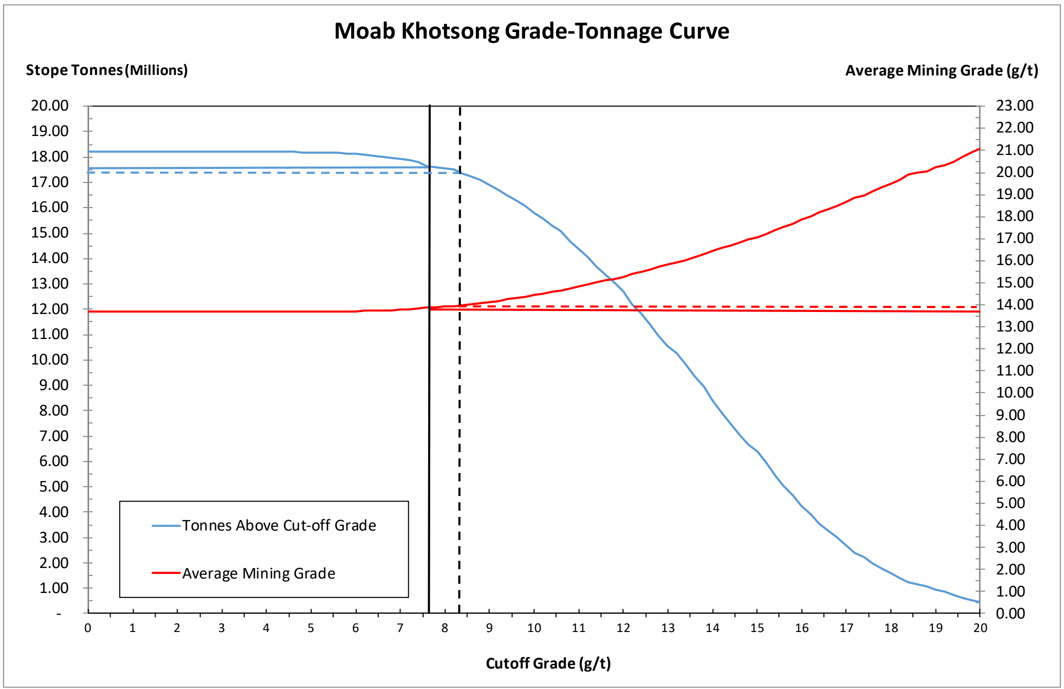

Figure 7-6. Moab Khotsong Mine grade-tonnage curve. Dashed lines represent the break-even approach, while solid lines represent the profit-optimised cut-off grade approach.

Table 7-XI. Moab Khotsong Mine break-even cut-off grade vs profit-optimised (with variable resource rate) cut-off grade.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	8.27	7.58	-8.34%
Total Stope Tonnes	Mt	17.43	17.66	1.29%
Total Milled Tonnes	Mt	21.96	22.24	1.29%
LoM	years	25	25	0.00%
AMG	g/t	13.96	13.88	-0.54%
Profit	US$ m	$2,910.00	$2,912.45	0.08%
NPV	US$ m	$933.86	$924.93	-0.96%
Total Revenue	US$ m	$10,248.27	$10,323.90	0.74%
Total Mining Costs	US$ m	($5,687.00)	($5,760.31)	1.29%
Total Royalties	US$ m	($416.14)	($416.71)	0.14%
Total Income Tax (gold tax)	US$ m	($1,235.12)	($1,234.43)	-0.06%
Total Tax Contribution	US$ m	($2,774.07)	($2,784.18)	0.36%

The profit increased by only 0.1% due to the reduction in the cut-off grade (US$2,910 to US$2,912 million). This reduction also slightly alters the mineral resource royalty and income tax rates, as shown in Table 7-XII.

Table 7-XII. Moab Khotsong Mine royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	4.06%	29.8%
Profit-optimised (variable royalty rate) cut-off grade	4.04%	29.8%

As can be observed in Tables 7-XI and 7-XII, the differences between the values generated by the two approaches at Moab Khotsong Mine are minor. This is surprising considering that the cut-off grade drops by 8.3% between the two approaches.

7.3.4 Free State Goldfield

Bambanani Mine

The grade-tonnage curve for Bambanani Mine is shown in Figure 7-7. This figure displays the relationship between the break-even and profit-optimised (variable royalty rate) cut-off grades, AMG and stope tonnes for the two approaches.

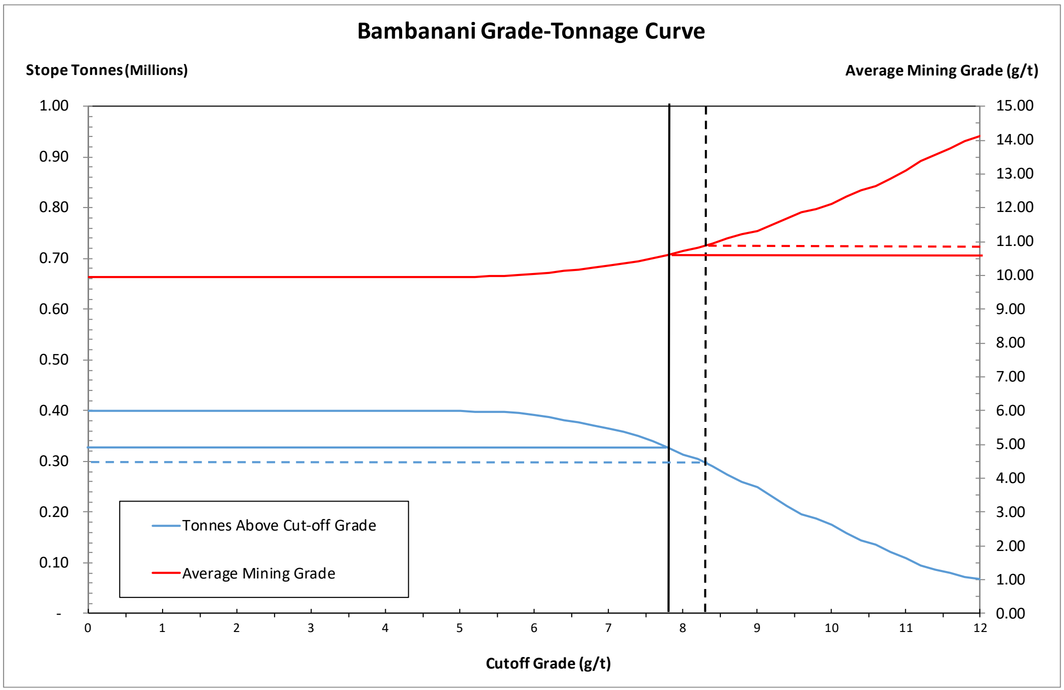

Figure 7-7. Bambanani Mine grade-tonnage curve. Dashed lines represent the break-even approach, while solid lines represent the profit-optimised cut-off grade approach.

The break-even grade (calculated including estimated royalty costs) is 8.29 g/t, whilst the profit-optimised (variable royalty rate) cut-off grade determined using the BirchOptimiser is 7.84 g/t (a reduction of 5.4%). The stope tonnes above the cut-off grade increase by 9.7% (0.297 to 0.325 million tonnes), and the AMG decreases from 10.88 to 10.63 g/t (a 2.3% drop). The profit increases 0.7% from US$26.34 to US$26.51 million. The analysis of the various approaches is shown in Appendix A2.7. Table 7-XIII shows the comparison between the base case and the profit-optimised approach.

Table 7-XIII. Bambanani Mine results of the base case break-even vs profit-optimised (with variable royalty rate) approaches.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	8.29	7.84	-5.43%
Total Stope Tonnes	Mt	0.30	0.33	9.85%
Total Milled Tonnes	Mt	0.35	0.38	9.85%
LoM	years	2	2	0.00%
AMG	g/t	10.88	10.63	-2.32%
Profit	US$ m	$26.34	$26.51	0.67%
NPV	US$ m	$22.64	$22.64	0.02%
Total Revenue	US$ m	$152.57	$163.70	7.30%
Total Mining Costs	US$ m	($112.63)	($123.73)	9.85%
Total Royalties	US$ m	($3.96)	($4.02)	1.49%
Total Income Tax (gold tax)	US$ m	($9.64)	($9.44)	-2.03%
Total Tax Contribution	US$ m	($29.76)	($30.93)	3.91%

The mineral resource royalty and income tax (gold tax formula) rates are shown in Table 7-XIV.

Table 7-XIV. Bambanani Mine royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	2.59%	26.79%
Profit-optimised (variable royalty rate) cut-off grade	2.46%	26.27%

Although the mineral resource royalty rate is lower for the profit-optimised (variable royalty rate) cut-off grade approach, the actual amount payable to the State increases from US$3.96 to US$4.02 million (a 1.5% increase). This is due to the 7.2% increase in revenue (US$152.6 to US$163.5 million). The income tax decreases by almost 2.0% (US$9.64 to US$9.45million). Due to the increased revenue and 9.7% increase in mining costs (US$112.6 to US$123.5 million), the additional taxes borne and employees' income taxes compensate for this (3.9%).

Beatrix Mine

The break-even grade for Beatrix Mine is estimated to be 5.48 g/t. The resultant AMG is 7.57 g/t, and the tonnes above this break-even grade are estimated to be 7,96 million. The profit-optimised (variable royalty rate) cut-off grade obtained from the BirchOptimiser is 5.16 g/t (5.8% reduction). This reduces the AMG by 3.8% to 7.28 g/t. There is a 14.8% increase in stope tonnes above this cut-off grade to 9.13 million. These are shown in the Beatrix Mine grade-tonnage curve (Figure 7-8).

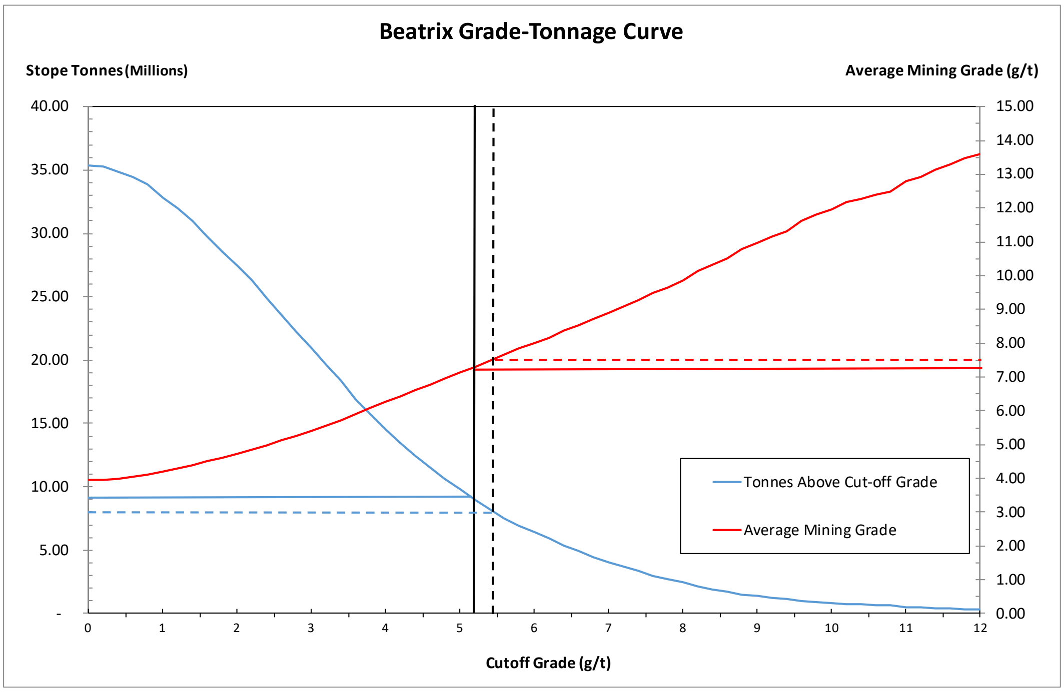

Figure 7-8. Beatrix Mine grade-tonnage curve. Dashed lines represent the break-even approach, while solid lines represent the profit-optimised cut-off grade approach.

When reducing the cut-off grade, the profit increases by 01% (US$478.1 to US$482.8 million). Appendix A2.8 contains the complete analysis of the various approaches, comparing the base case break-even and profit-optimised (with variable royalty rate) cut-off grade presented in Table 7-XV.

Table 7-XV.Beatrix Mine optimisation comparison results.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	5.48	5.16	-5.84%
Total Stope Tonnes	Mt	7.96	9.16	15.05%
Total Milled Tonnes	Mt	8.68	9.98	15.05%
LoM	years	5	6	20.00%
AMG	g/t	7.57	7.27	-3.88%
Profit	US$ m	$478.06	$482.81	0.99%
NPV	US$ m	$348.48	$339.23	-2.65%
Total Revenue	US$ m	$2,423.72	$2,680.29	10.59%
Total Mining Costs	US$ m	($1,691.09)	($1,945.62)	15.05%
Total Royalties	US$ m	($70.73)	($72.17)	2.04%
Total Income Tax (gold tax)	US$ m	($183.84)	($179.68)	-2.26%
Total Tax Contribution	US$ m	($516.86)	($545.06)	5.45%

The changes to the mineral resource royalty and income tax rates are shown in Table 7-XVI.

Table 7-XVI. Beatrix Mine royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	2.92%	27.78%
Profit-optimised (variable royalty rate) cut-off grade	2.70%	27.13%

The total revenue for the mine increased by 10.4% (US$2,424 to US$2,676 million) with the reduced cut-off grade, which significantly increased the total tax contribution to the State (6.8%). The mining costs increased by 14.8% (US$1,691 to US$1,941 million). The mineral resource royalty cost increases from US$70.73 to US$72.16 million (a 2.0% increase), whilst the income tax reduces by 2.2% (US$183.8 to US$179.8 million). Overall, the total tax contribution increases by 5.5%.

Joel Mine

A 4.9% drop in the profit-optimised (variable royalty rate) cut-off grade (4.61 g/t) compared to the break-even grade (4.91 g/t) results in a 5.7% increase in stope tonnage above the cut-off grade (5.66 to 5.98 million tonnes). The AMG drops by 1.8% (7.09 to 6.96 g/t). These are shown in Figure 7-9. The complete analysis of the various approaches can be found in Appendix A2.9.

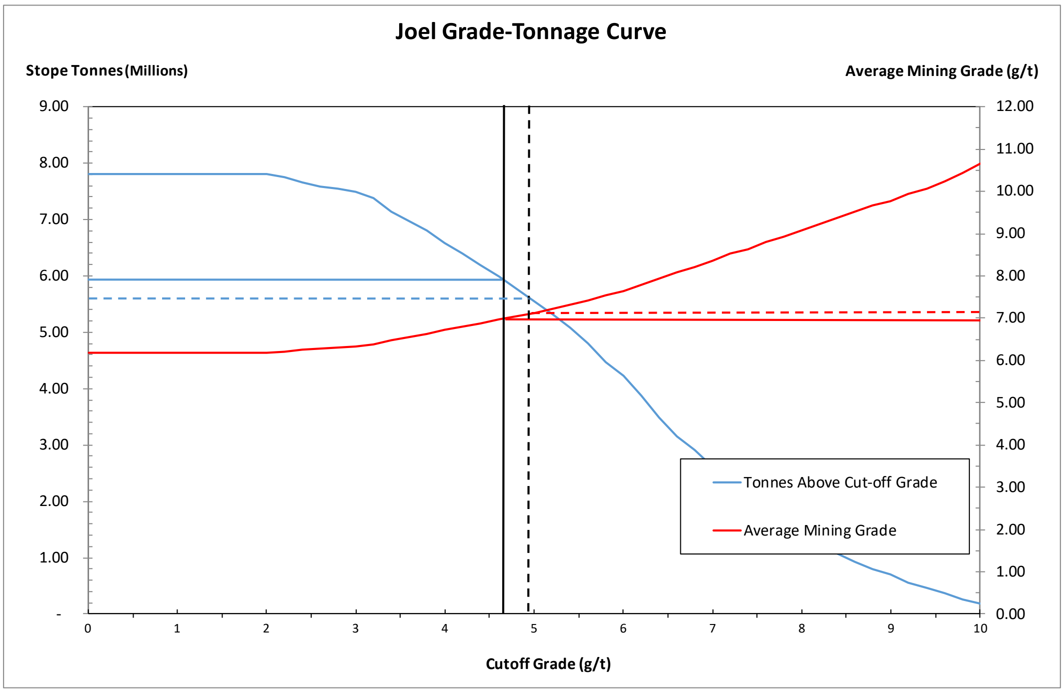

Figure 7-9. Joel Mine grade-tonnage curve. Dashed lines represent the break-even approach, while solid lines represent the profit-optimised cut-off grade approach.

There is an increase in the profit determined by the BirchOptimiser from US$399.2 to US$400.6 million (0.4%). This increase, however, does not take into account the savings from the expected increase in stope tonnes from the development that will occur as more of the ore body is utilised. The comparison between the base case break-even vs cut-off grade analysis is shown in Table 7-XVII.

Table 7-XVII.Joel Mine break-even vs profit-optimised (with variable royalty rates) cut-off grade comparison.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	4.91	4.61	-6.11%
Total Stope Tonnes	Mt	5.66	5.98	5.65%
Total Milled Tonnes	Mt	6.18	6.53	5.65%
LoM	years	18	19	5.56%
AMG	g/t	7.09	6.96	-1.76%
Profit	US$ m	$399.21	$400.62	0.35%
NPV	US$ m	$165.79	$160.20	-3.37%
Total Revenue	US$ m	$1,830.56	$1,899.98	3.79%
Total Mining Costs	US$ m	($1,214.40)	($1,283.07)	5.65%
Total Royalties	US$ m	($58.45)	($58.85)	0.70%
Total Income Tax (gold tax)	US$ m	($158.50)	($157.44)	-0.67%
Total Tax Contribution	US$ m	($417.96)	($426.21)	1.97%

The changes in cut-off grade result in a 3.8% increase in total revenue (US$1,831 to $1,901 million). The mining costs increase by 5.7% (US$1,214 to US$1,284 million). Table 7-XVIII shows the changes in the mineral resource royalty and income tax rates that would result from the change in cut-off grade.

Table 7-XVIII. Joel Mine royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	3.19%	28.42%
Profit-optimised (variable royalty rate) cut-off grade	3.10%	28.21%

Although the mineral resource royalty rate drops, the actual royalty cost increases by 0.7%, from US$58.45 to US$58.86 million. There is a 0.7% decrease in the income tax calculated using the gold tax formula from US$158.5 to US$157.4 million. The total tax contribution, however, increases due to the increased production (2.0%).

Masimong Mine

Table 7-XIX shows the results of the base case break-even compared to the profit-optimised (variable royalty rate) approaches.

Table 7-XIX. Masimong Mine break-even vs profit-optimised cut-off grade comparison.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	6.43	6.11	-4.98%
Total Stope Tonnes	Mt	1.31	1.43	8.87%
Total Milled Tonnes	Mt	1.44	1.57	8.87%
LoM	years	3	4	33.33%
AMG	g/t	8.13	7.98	-1.88%
Profit	US$ m	$51.58	$51.92	0.64%
NPV	US$ m	$41.58	$41.35	-0.55%
Total Revenue	US$ m	$334.42	$357.25	6.83%
Total Mining Costs	US$ m	($257.01)	($279.81)	8.87%
Total Royalties	US$ m	($7.86)	($7.98)	1.48%
Total Income Tax (gold tax)	US$ m	($17.96)	($17.54)	-2.32%
Total Tax Contribution	US$ m	($63.74)	($66.15)	3.78%

A comprehensive analysis of the different approaches can be found in Appendix A2.10. Table 7-XX shows the mineral resource royalty and income tax changes between the two approaches.

Table 7-XX. Masimong Mine royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	2.35%	25.83%
Profit-optimised cut-off grade	2.24%	25.29%

The total revenue increased from US$334.4 to US$355.9 million (6.4%), whilst the total mining costs increased from US$257.0 to US$278.4 million (8.3%). This significantly increases the total tax contribution (3.8%) from the mine and offsets the reduction in total direct tax revenue (US$25.8 to US$25.6 million, which is -1.0%).

The Masimong Mine grade tonnage curve is displayed in Figure 7-10.

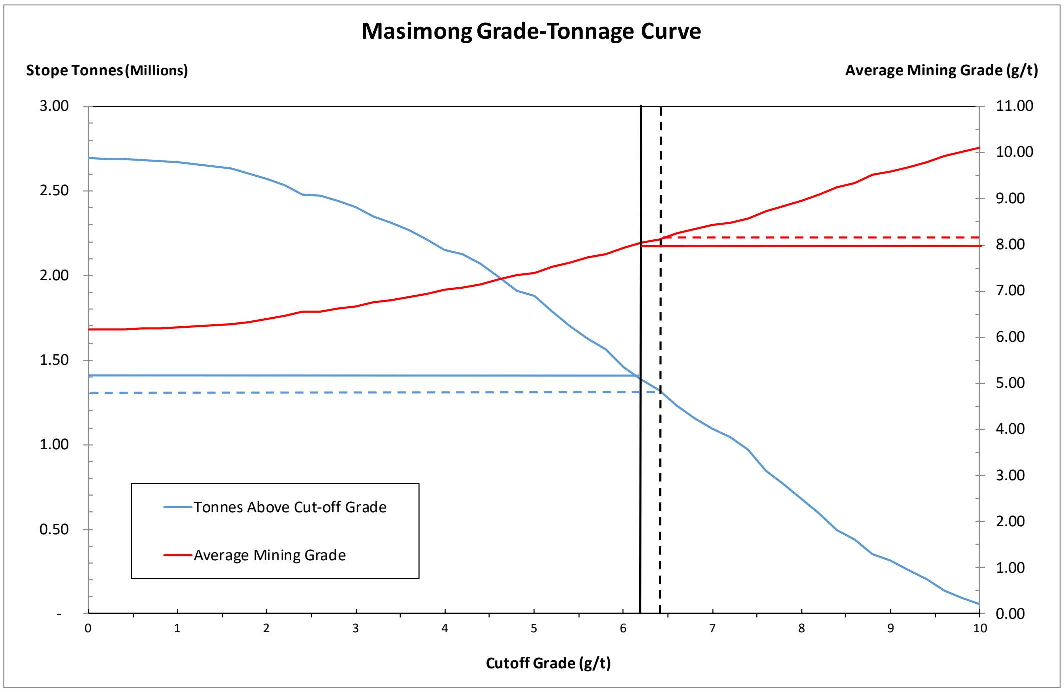

Figure 7-10. Masimong Mine grade tonnage curve. Dashed lines represent the break-even approach, while solid lines represent the profit-optimised cut-off grade approach.

From the grade-tonnage curve, the break-even grade of 6.43 g/t results in 1.31 million tonnes above this grade. The AMG is 8.13 g/t. The lower profit-optimised (variable royalty rate) cut-off grade is 6.11 g/t. This is a reduction of 4.9%. This reduction increases the tonnage above this grade by 8.3% to 1.42 million tonnes. The AMG is 1.8% lower at 7.99 g/t.

Tshepong Mine

The break-even grade (including estimated royalty costs) for the Tshepong mine was estimated to be 6.19 g/t. The profit-optimised (variable royalty rate) cut-off grade determined by the BirchOptimiser is 5.67 g/t. This is an 8.4% reduction. Figure 7-11 shows the grade-tonnage curve for Tshepong Mine.

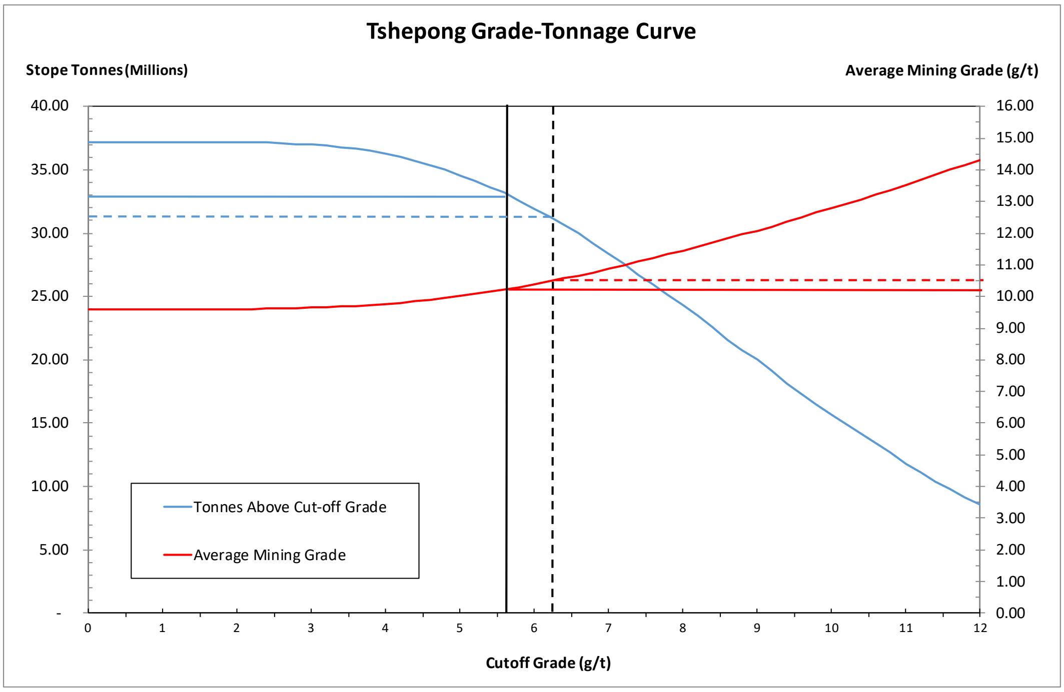

Figure 7-11.Tshepong Mine grade-tonnage curve. Dashed lines represent the break-even approach, while solid lines represent the profit-optimised cut-off grade approach.

The stope tonnes above the cut-off grade for the two approaches are 31.32 and 32.95 million tonnes, respectively (5.2% increase). The AMG for the break-even calculated grade is 10.47 g/t, while the AMG determined by the profit-optimised (variable royalty rate) approach is 10.25 g/t (2.1% lower). The complete analysis for Tshepong Mine for all the different approaches is in Appendix A2.11. Table 7-XXI shows the results of the base case and profit-optimised approaches.

Table 7-XXI. Base case break-even vs profit-optimised cut-off grade analysis results.

Value	Unit	Break-Even Base Case	Variable Rate Profit-optimised	Differences
Cut-off Grade	g/t	6.19	5.67	-8.40%
Total Stope Tonnes	Mt	31.32	32.93	5.15%
Total Milled Tonnes	Mt	37.97	39.92	5.15%
LoM	years	25	26	4.00%
AMG	g/t	10.47	10.25	-2.12%
Profit	US$ m	$3,751.91	$3,762.90	0.29%
NPV	US$ m	$1,201.85	$1,156.61	-3.76%
Total Revenue	US$ m	$13,168.40	$13,552.99	2.92%
Total Mining Costs	US$ m	($7,286.48)	($7,661.64)	5.15%
Total Royalties	US$ m	($536.40)	($539.07)	0.50%
Total Income Tax (gold tax)	US$ m	($1,593.62)	($1,589.37)	-0.27%
Total Tax Contribution	US$ m	($3,519.64)	($3,568.02)	1.37%

Table 7-XXII shows the differences in mineral resource royalty and income tax rates for the two approaches.

Table 7-XXII. Tshepong Mine royalty and income tax rates comparison.

Approach	Royalty Rate	Gold Tax Rate
Break-even grade with est. royalty costs	4.07%	29.81%
Profit-optimised (variable royalty rate) cut-off grade	3.98%	29.69%

Although the mineral resource royalty rate is lower for the profit-optimised (variable royalty rate) cut-off grade approach, the amount payable is 0.5% higher (US$536.4 to US$539.1 million). This is due to the 2.95% increase in revenue (US$13,168 to US$13,557 million). The income tax drops by 0.5% (US$1,594 to US$1,589 million), but the overall 0.3% reduction in direct tax revenue by the State would is offset by a higher total tax contribution (1.4%). There is a 5.2% increase in mining costs from US$7,286 to US$7,666 million.

7.4 Benefits of Removing Royalty Costs from Cut-off Grade Calculation

The benefits of removing the royalty costs from the break-even grade calculation or adopting the BirchOptimiser approach are demonstrated in the following graphs, which present the combined findings for the eleven mines reviewed. The average break-even/cut-off grade is weighted using the total tonnes above the break-even/cut-off grade. The rationale for presenting the break-even cut-off grade (excluding royalty) approach results is that the mines could quickly adopt this without changing their current approach in determining their cut-off grades. However, further benefits could be derived by adopting the BirchOptimiser profit-optimised (with variable royalty rate) approach that takes the interplay of the mineral resource royalty and the gold tax profitability into account when determining the cut-off grade. This approach is shown to be the best when the overall profit is used as a value measure. The NPV_{12} figures are also presented for the study but optimising to maximise the NPV has been shown to reduce the LoM and total resource utilisation severely. The details of all the various analyses are presented in Appendix 2.

7.4.1 Stope tonnes above the cut-off grade

Figure 7-12 shows the difference in the overall tonnes above the cut-off grade for the three approaches.

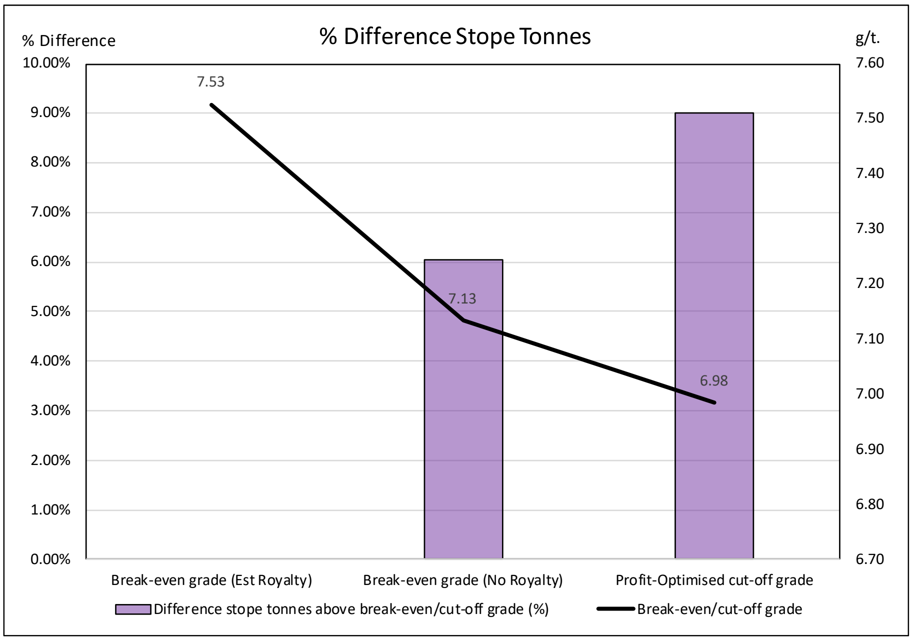

Figure 7-12. Percentage difference in stope tonnes above the break-even/cut-off grade between base-case (break-even grade including royalty costs), break-even grade excluding royalty costs and profit-optimised cut-off grade (using variable royalty rate).

It can be observed in Figure 7-12 that using the break-even grade (excluding royalties) as the cut-off grade increases the tonnes above the cut-off grade by 6% of the break-even grade (including royalties). An additional 3% can be mined if the profit-optimised (with variable royalty rate) approach is adopted (as determined using the BirchOptimiser).

7.4.2 Profit

Figure 7-13 shows the profit difference using the three approaches.

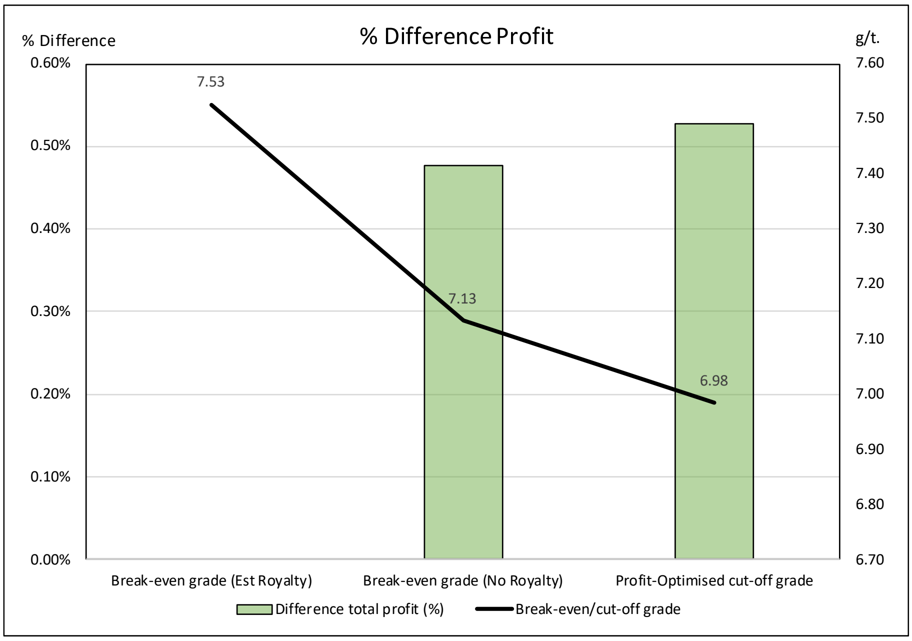

Figure 7-13. Percentage difference in profit between base-case (break-even grade including royalty costs), break-even grade excluding royalty costs and profit-optimised cut-off grade (using variable royalty rate).

The difference in overall profit between the three approaches is very slight, with only an additional 0.5% being gained by adopting the profit-optimised (with variable royalty rate) approach. However, the benefits need to consider a broader view of value than profit when considering the South African situation of extremely high unemployment.

7.4.3 Resource utilisation

An additional benefit to the profit of the mine can, however, be seen in the light of increased resource utilisation. Figure 7-14 shows how the percentage of resource utilisation increases as the cut-off grade is reduced by excluding the royalty costs in the calculation and using the profit-optimised (using variable royalty rate) approach.

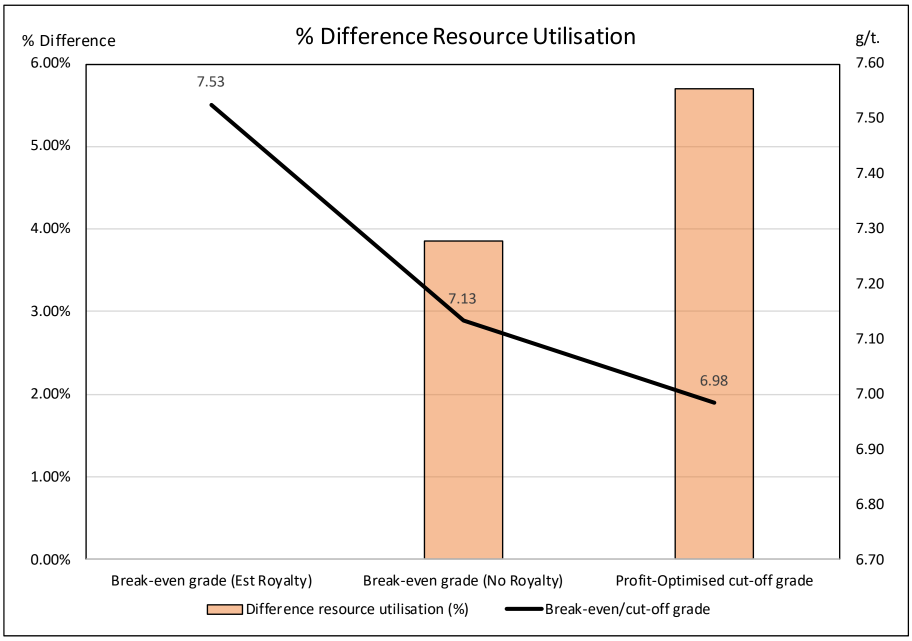

Figure 7-14. Percentage difference in resource utilisation (kilograms) between base-case (break-even grade including royalty costs), break-even grade excluding royalty costs and profit-optimised cut-off grade (using variable royalty rate).

There is a 3.9% and 5.7% increase in resource utilisation (in kilograms) noted between the two approaches compared to the base-case approach. This is significant because it would allow greater ore mining from the same input capital costs. One of the planning methods used in South African gold mines is the "iceberg" (School of Mining Engineering, 2021a). This method determines how much main footwall haulage development is required to ensure sufficient mining face is opened to meet the business plan. One of the key inputs into this calculation is the expected resource utilisation (considering cut-off grade and aspects like mining method and geological losses). Increasing the resource utilisation by up to 5.7% would bring significant savings in development costs, reducing the AISC. Figure 7-15 demonstrates how increasing the resource utilisation (through lower cut-off grade) reduces development requirements and costs and further lowers the cut-off grades.

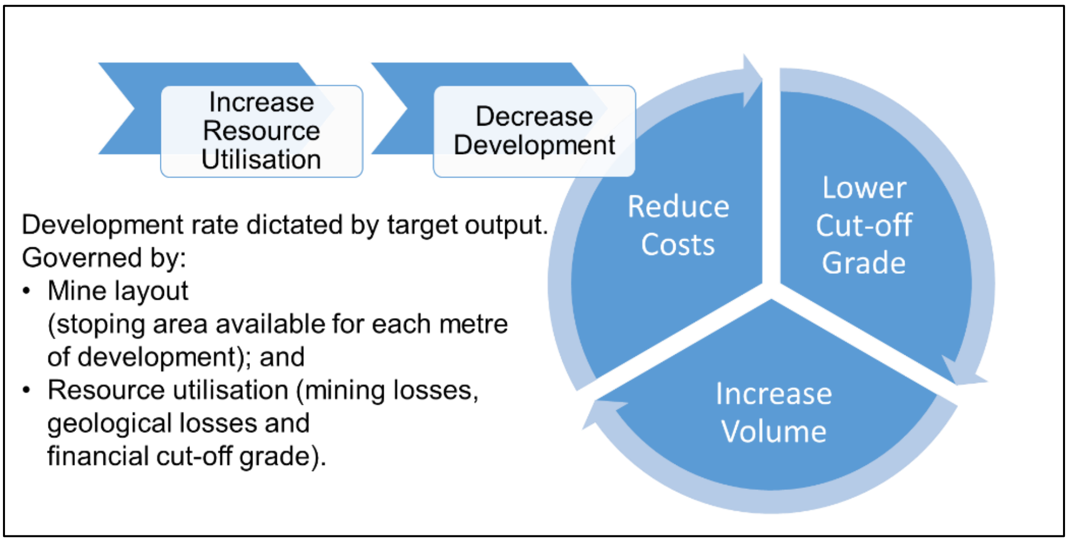

Figure 7-15. The spiral effect of reducing costs leading to lower cut-off grades.

7.4.4 Total revenue

Figure 7-16 shows the increase in the total revenue obtained by adopting either the break-even (excluding royalty cost) or the profit-optimised (with variable royalty rate) approach.

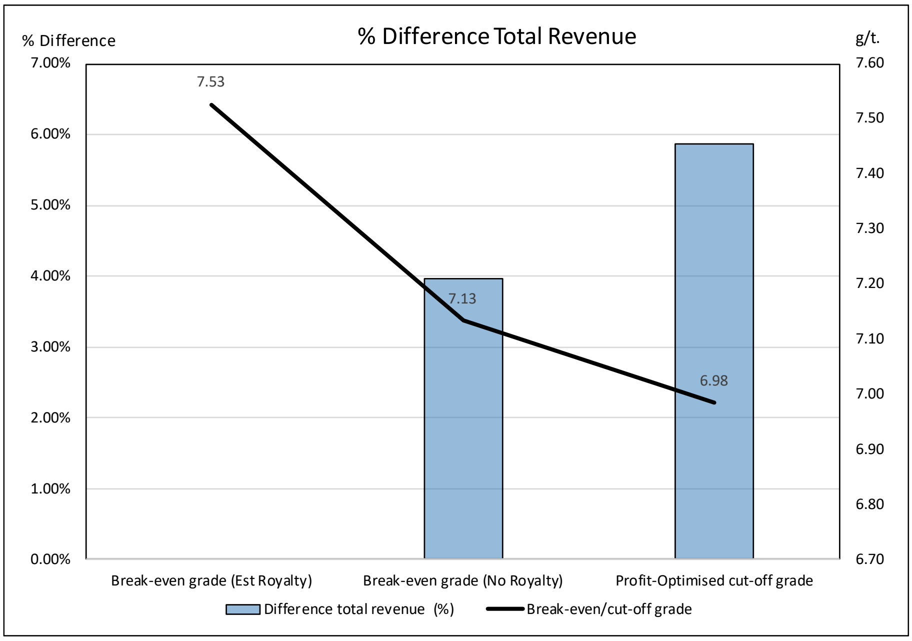

Figure 7-16. Percentage difference in total revenue between base-case (break-even grade including royalty costs), break-even grade excluding royalty costs and profit-optimised cut-off grade (using variable royalty rate).

Figure 7-16 shows that the total revenue from the mines reviewed could be increased by 4% and 5.9%, respectively, by adapting either the break-even (excluding royalty cost) or the profit-optimised (with variable royalty rate) approach. Considering the importance of mining to the overall economy of South Africa, demonstrating that there is a benefit in excluding the royalty costs from the cut-off grade calculations is considered very important. Although this approach has only been applied to gold mines, many other commodities apply break-even and cut-off optimisation approaches. Although they would not enjoy the benefit that a reduced profitability ratio would have on their corporate income tax rate (fixed at 27%), the benefit the reduced profitability has on the mineral resource royalty rate is expected to be the same.

7.4.5 Total tax contribution

The calculations used in this study have included income tax (determined by the gold tax formula) and mineral resource royalty. However, these are not the only sources of revenue that the State derives from mining. The weighted average labour costs for the mines reviewed (using total mining costs) show that labour costs contribute about 56% of the total mining costs (S&P Capital IQ, 2021). Salaries relate to the remuneration paid to workers and exclude the employer's contributions to personnel funds, such as a pension, medical and holiday funds, and training and recruitment costs (Langbein & Weber, 2018). The employees' salaries represent approximately half the total labour costs (Meredith, personal communication, 25 June 2022). Employees' income tax (based on the labour cost for each of the mines compared to the total cost) is estimated at 18% of the employees' salaries, representing the entry-level tax rate (South African Revenue Service, 2022; Talent.com, 2022). These figures are considered conservative, and the actual contribution that employees' income taxes make could be significantly higher. The energy costs contribute about 13% of the total mining costs, whilst the other production costs and royalties make up the balance (31%). Considering that an estimated 7.5% of a mines total revenue can be attributed to tax contributions borne (Ralbovsky & Symons, 2010), this has been used to establish the total tax contribution. Figure 7-17 considers the total estimated taxes collected (royalty, income tax and employees' income tax) and additional taxes borne to determine the overall estimated total tax contribution.

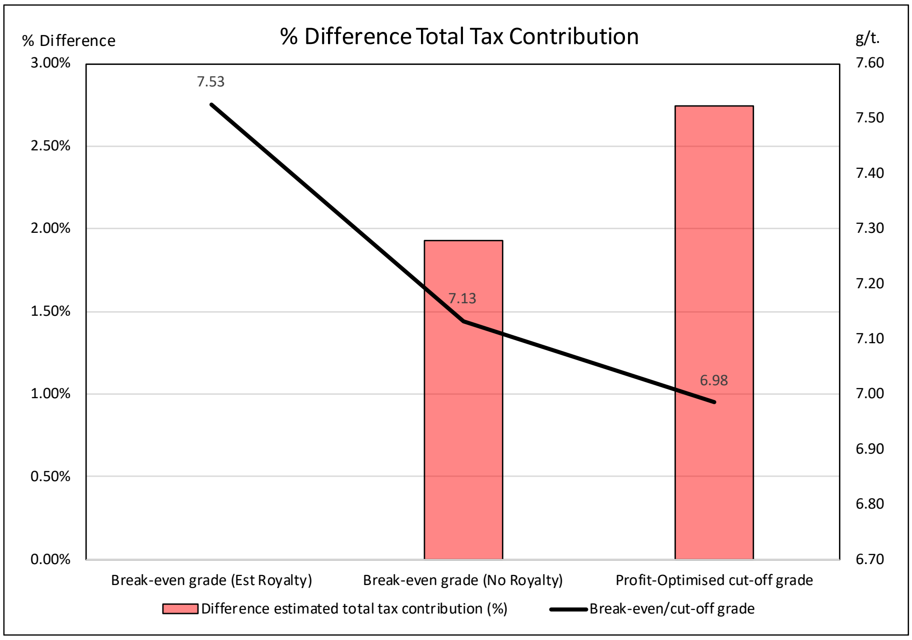

Figure 7-17. Percentage difference in total tax contribution between base-case (break-even grade including royalty costs), break-even grade excluding royalty costs and profit-optimised cut-off grade (using variable royalty rate).

Figure 7-17 shows that even though the royalty rate (weighted average of 3,6% to 3,5% to 3.4% for the three approaches) and income tax rates (weighted average of 29.0% to 28.8% to 28.7% for the three approaches) drop, the overall total tax contribution increases due to the higher turnover from the mines. This overall tax contribution increase for the break-even (excluding royalty cost) is estimated to be 1.9% and 2.8% for the profit-optimised (with variable royalty rate) approach.

7.5 Chapter Summary

It was shown in the initial 2016 study for this research project that the introduction of the South African mineral resource royalty in 2010 is potentially having a detrimental effect on the economic lives of the gold mines of the country (Birch, 2016a). This study identified that the mines included royalty costs when determining the cut-off grade. The base case for the various comparisons presented in this section is a break-even cut-off grade approach with the estimated royalty costs included as a mining cost (for which the AISC has been used). However, it is shown in this current study that the optimal way to deal with this royalty cost in the cut-off grade calculation is to ignore it or only consider the 0.5% as an additional cost. The rest of the royalty cost should be considered the same as a profit-based tax.

The BirchOptimiser developed for this study into the impact of the mineral resource royalty costs and identifying the preferred approach to consider these costs when calculating cut-off grades also lends itself to other investigations. The following chapter uses the BirchOptimiser as a foundation for two new approaches to cut-off grade optimisation. These are cut-off grade optimisation considering grade uncertainty and a multiple-criteria cut-off grade approach.

8 NEW APPROACHES TO CUT-OFF GRADE OPTIMISATION

8.1 Introduction

This chapter presents two new approaches to cut-off grade optimisation. The first approach considers how some of the value lost due to grade estimation can be recovered by adjusting the cut-off grade to reduce either dilution or lost ore.

It has been shown in the previous section how the cut-off grade selected for maximising the NPV is significantly higher than the cut-off grade to maximise profit. This has a very detrimental effect on the overall resource utilisation and shortens the life of the mine. The second new approach uses the flexibility of the BirchOptimiser to maximise different value measures in addition to profit or NPV optimisation. A multiple-criteria approach is outlined where the cut-off grades to maximise total direct revenue to the State, and a predetermined profitability ratio is also determined. A weighted average cut-off grade is then determined.

8.2 Managing Grade Estimation Uncertainty with the Cut-Off Grade

8.2.1 Section introduction

"Any resource or reserve estimate is guaranteed to be wrong. Some, however, are less wrong than others" (Rozman, 1998). Morley et al. (1999) identified that the resource is the primary input into any feasibility study or mine financial analysis, which can be assumed to be wrong. It is not uncommon for projects to have cost and revenue estimate uncertainties quoted (commodity price, capital and operating expenses) and even assessed using Monte Carlo simulation to determine the overall impact (Morley, Snowden & Day, 1999). While some companies take great pride in exceeding the production and revenue estimates by a significant margin,

this could indicate that their estimation methodologies are very poor (Morley, Snowden & Day, 1999).

This section presents an approach to managing uncertainty in the estimated grade value for the blocks. When applying a cut-off grade to determine an ore block value, the assumption is that the estimated and actual values are the same. The overall difference between these two grades is considered during the cut-off grade calculation by including the MRF. However, a financial value can be obtained by understanding the uncertainty associated with the estimation and the overall estimation bias and managing this through cut-off grade optimisation.

Optimization of cut-off grades considering grade uncertainty in narrow, tabular gold deposits (Birch, 2017) was published and was the initial investigation and development of the approach presented here. In the initial investigation, the distribution of the uncertainty was considered normal. The extent of the uncertainty was varied by altering the standard deviation and observing the impact on the profit and $NPV_{9\%}$ and $NPV_{12\%}$ results. It demonstrated that it was financially beneficial to lower the cut-off grades in some instances.

8.2.2 Block Grade Uncertainty

In statistics, accepting a hypothesis when it should have been rejected is a type I error. The alternative error is rejecting a hypothesis when it should have been accepted. This is called a type II error (Underhill & Bradfield, 1994). Due to uncertainty in estimation, the same two errors can occur. The type I error is where the material is classified as ore and mined. However, the true value is below the cut-off grade and thus is waste material. This material is dilution. The type II error is where the material is estimated to be below the cut-off grade; therefore, it is classified as waste where the actual grade is above the cut-off grade. This material is not mined and is lost (Minnitt, 2017)

The question is raised as to what adjustment should be made to the cut-off grade to reduce the financial impact of dilution or lost ore in typical narrow, tabular Witwatersrand gold mines. There are three options available, and these are as follows:

- Raise the cut-off grade to reduce the dilution (*"the old adage that a low-grade ton should never keep a high-grade ton out of the mill"* (Minnitt, 2017) ;
- Keep cut-off grades the same, considering that the type I and type II errors would balance each other if there is no bias; or
- Lower cut-off grades to ensure all value from the orebody is obtained (thus recovering a higher percentage of the lost ore).

The estimated value for a mining block and the true value would be the same in an ideal world. There would be no blocks estimated to be above the cut-off grade that is actually below the cut-off grade (type I error or dilution). There would also be no blocks estimated to be below the cut-off grade that is actually above the cut-off grade (type II error or lost ore). This ideal relationship is shown in Figure 8-1.

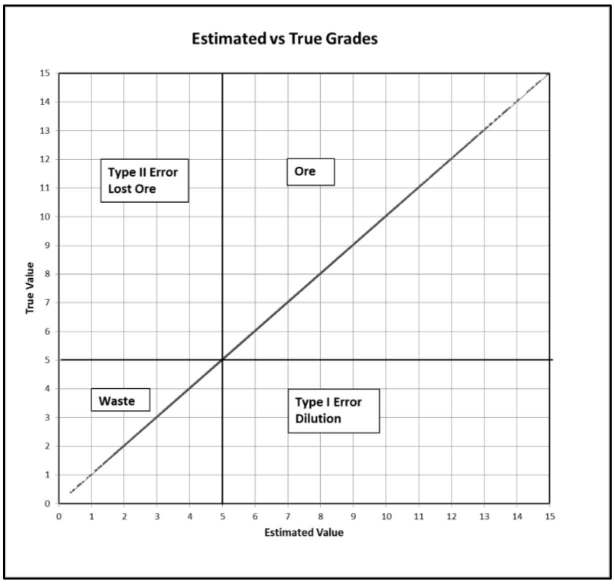

Figure 8-1. In an ideal world where estimated and true values are the same (0% uncertainty). All data points plot along a single line. No dilution or lost ore occurs. Cut-off grade 5 g/t.

This is, however, not reality. The quality and accuracy of the sampling and estimation techniques affect the uncertainty. Low uncertainty is shown in Figure 8-2, and high uncertainty in Figure 8-3. There are also limitations related to the cost of sampling and that an actual grade will ultimately only be determined after all the material has been mined and milled.

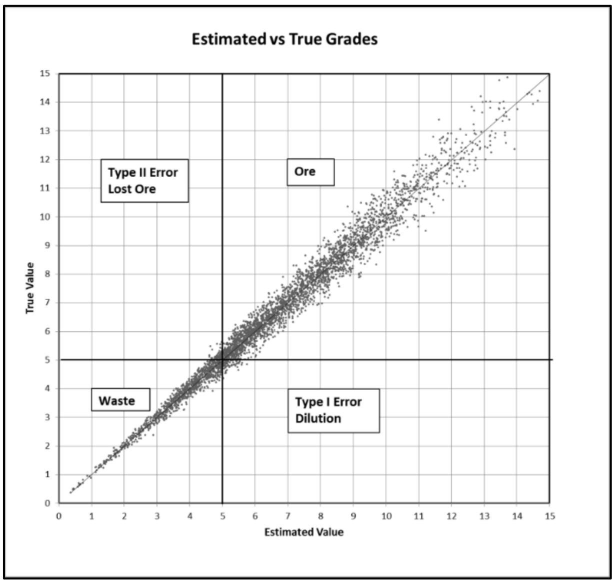

Figure 8-2. High-quality sampling and estimation results in minimal dilution and lost ore considering a 5 g/t cut-off grade.

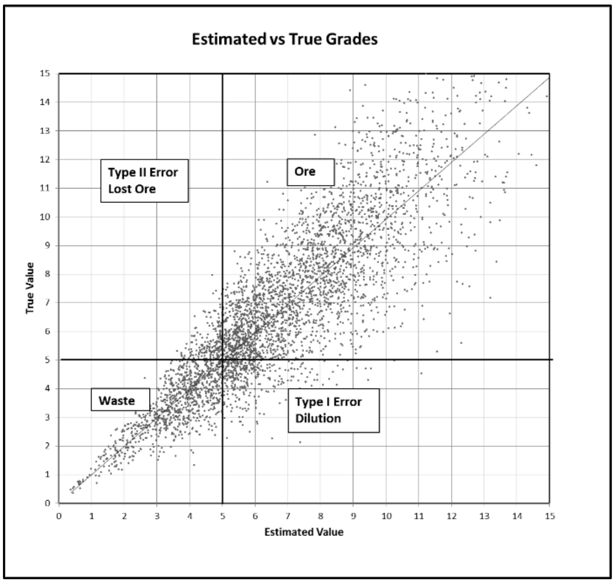

Figure 8-3. Low-quality sampling and estimation results in significant dilution and lost ore considering a 5 g/t cut-off grade.

Minnitt (2017) investigated the financial outcomes of poor sampling and grade distributions. For gold deposits, he found that a 10% sampling error has a negligible impact on the value of the deposit. However, he found positive and negative bias to significantly impact value (Minnitt, 2017).

8.2.3 Gold Mine Case Study

The initial study (Birch, 2017) assumed that the uncertainty follows a normal distribution and that there is no bias present in the estimations. It was broadly found that reducing the cut-off grade improves the financial returns with higher degrees of uncertainty. This study considers the 'actual' grade uncertainty for four South African gold mines and determines how the cut-off grades should be adjusted for the eleven gold mines researched for this thesis. There has been no consideration for bias for this approach, and the simulated block listings have been set up assuming a block factor of 100%.

Sources of data

For this study, the pre-mining estimated and post-mining 'actual' block grades were obtained from four mines (from the West Wits and Free State goldfields). Note that the 'actual' block grades are still an estimation. They are just considered the best estimate of the block value after mining. When determining the MRF, these are the values used as the basis for the "gold called for" by the surveyor. The overall variance from these 'actual' block values and the true value for the monthly period being reviewed is dealt with in determining the cut-off grade by including the MRF in the calculation.

The number of blocks included in the analysis ranged from 1,757 to 2,547 for the respective mines. The estimated grades vs the 'actual' grades for the four mines' are shown in Figure 8-4.

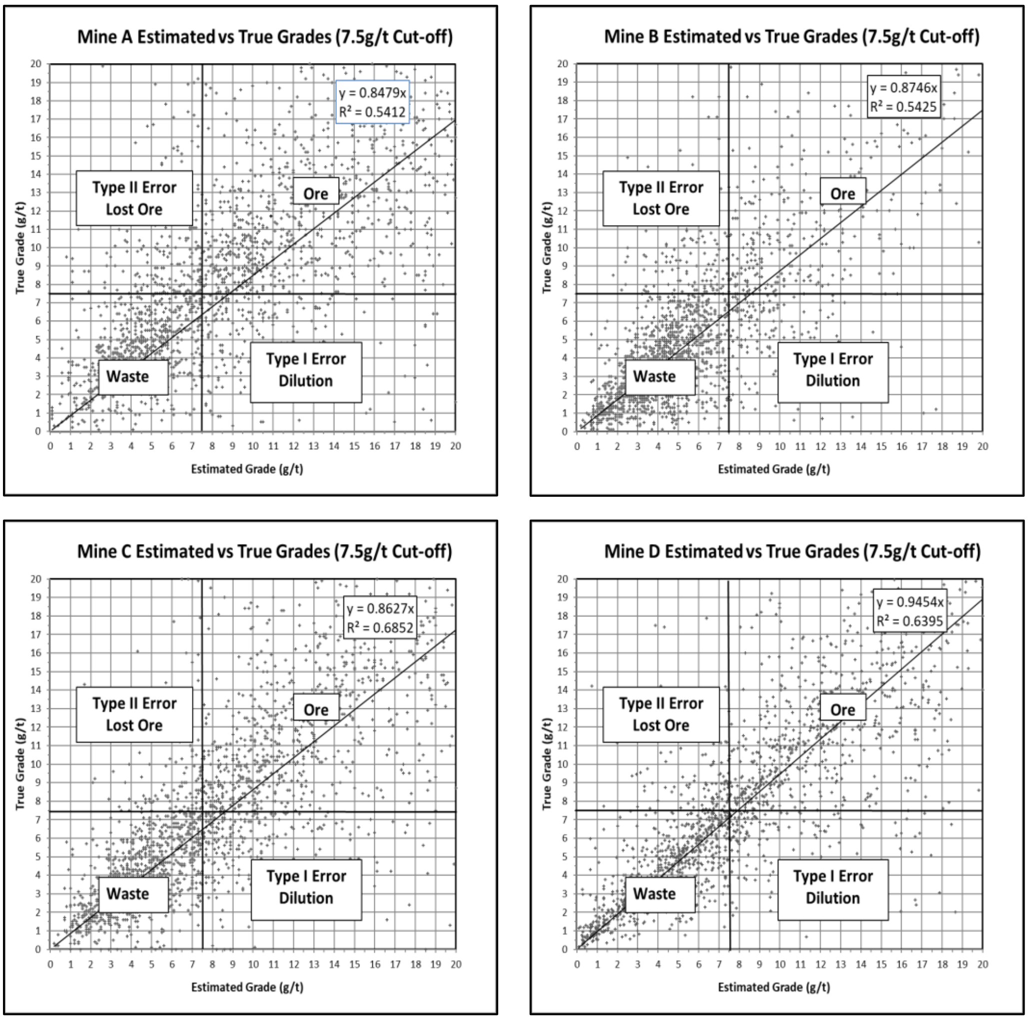

Figure 8-4. Pre-mining estimated vs post-mining 'actual' block grades for the four mines.

It can be observed that there is significant over-valuation in the estimated block grades for three of the mines. This is reflected in the slope of the trend lines. For Mine A, the slope is 0.85, Mine B is 0.87, and Mine C is 0.86. This is significant because it shows a clear bias in the estimation. The bias is far less for Mine D, and the slope is 0.95.

Variation distribution

The distribution of these variations is analysed using the Palisade @Risk Distribution Fit tool, which is found to be Laplace distributions. The Laplace distribution has a higher peak than a normal distribution and two very heavy tails, also called the double exponential distribution. It can be viewed as two exponential distributions spliced back to back (Hilali, 2016).

The distribution that best fits the data was determined from the Akaike information criterion value. The Akaike information criterion compares a model's relative “quality” (distribution) versus the other models. @Risk ranks the various distribution model outputs according to this value, and the distribution with the smallest Akaike information criterion value is usually the preferred model (BPI Consulting, 2016). Figure 8-5, 8-6, 8-7 and 8-8 shows the four mines' Laplace and normal distribution curves.

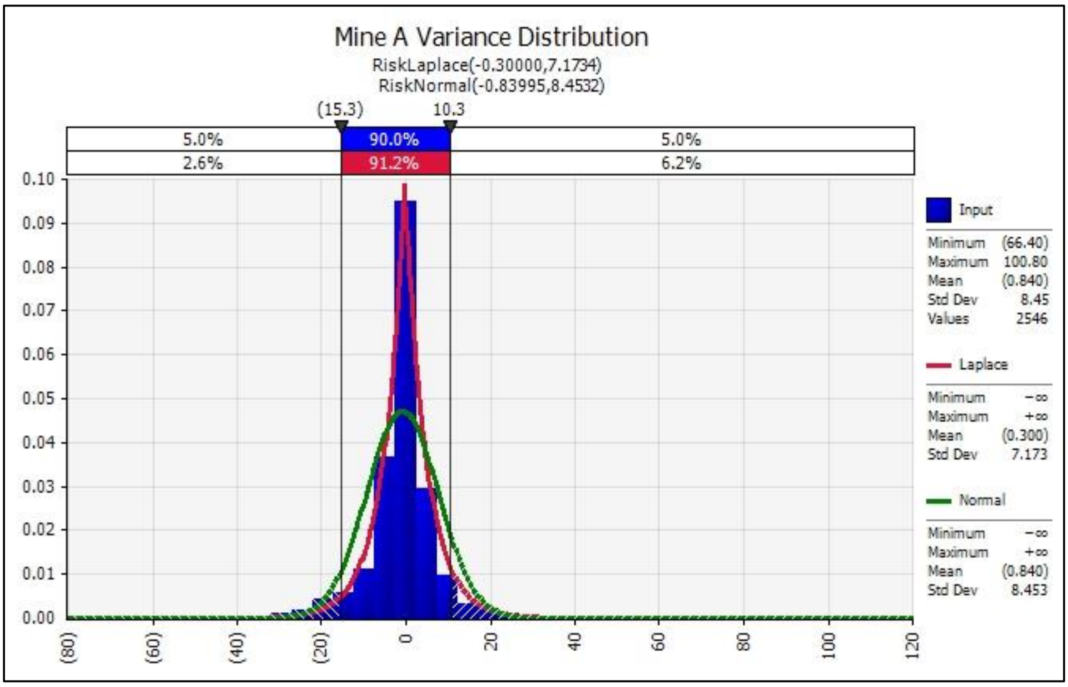

Figure 8-5. Mine A variance distribution.

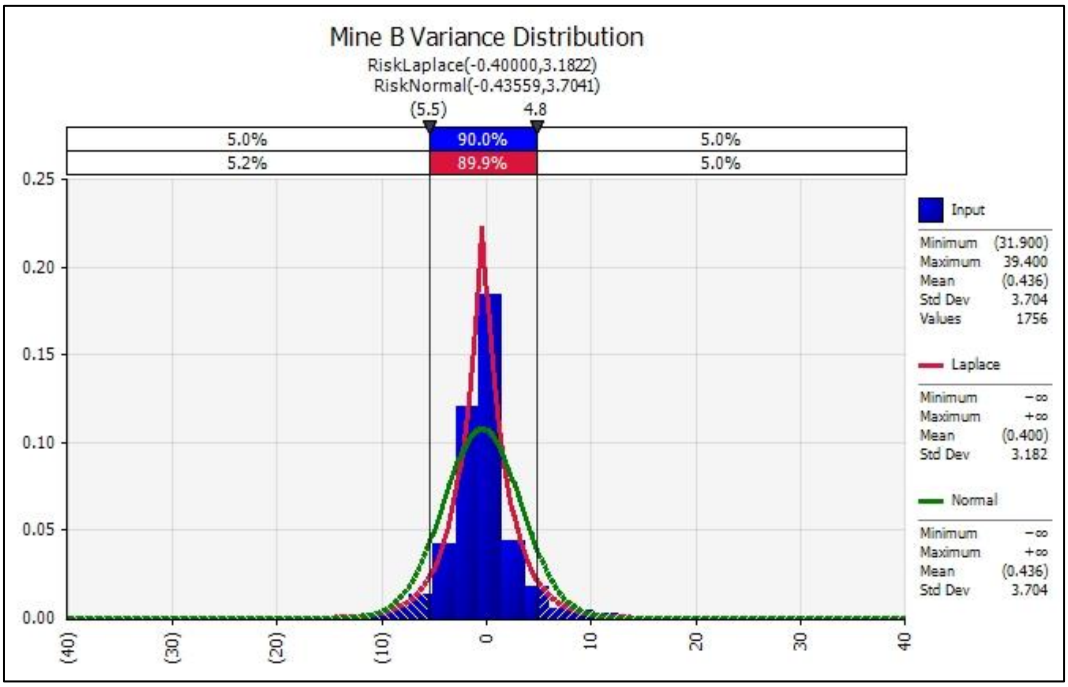

Figure 8-6. Mine B variance distribution.

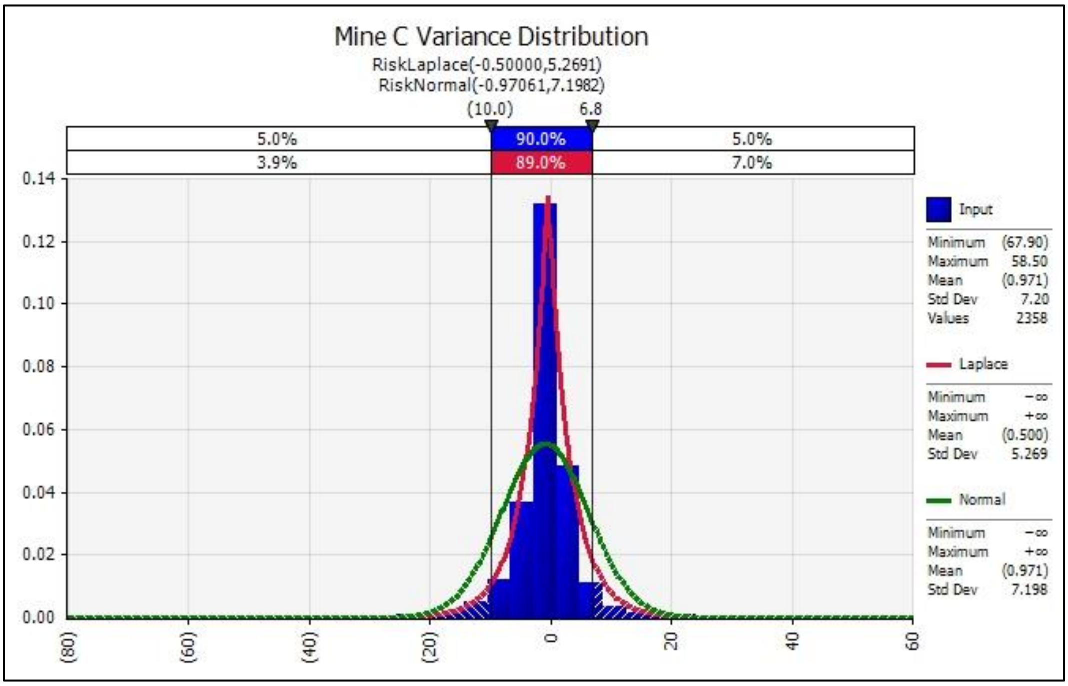

Figure 8-7. Mine C variance distribution

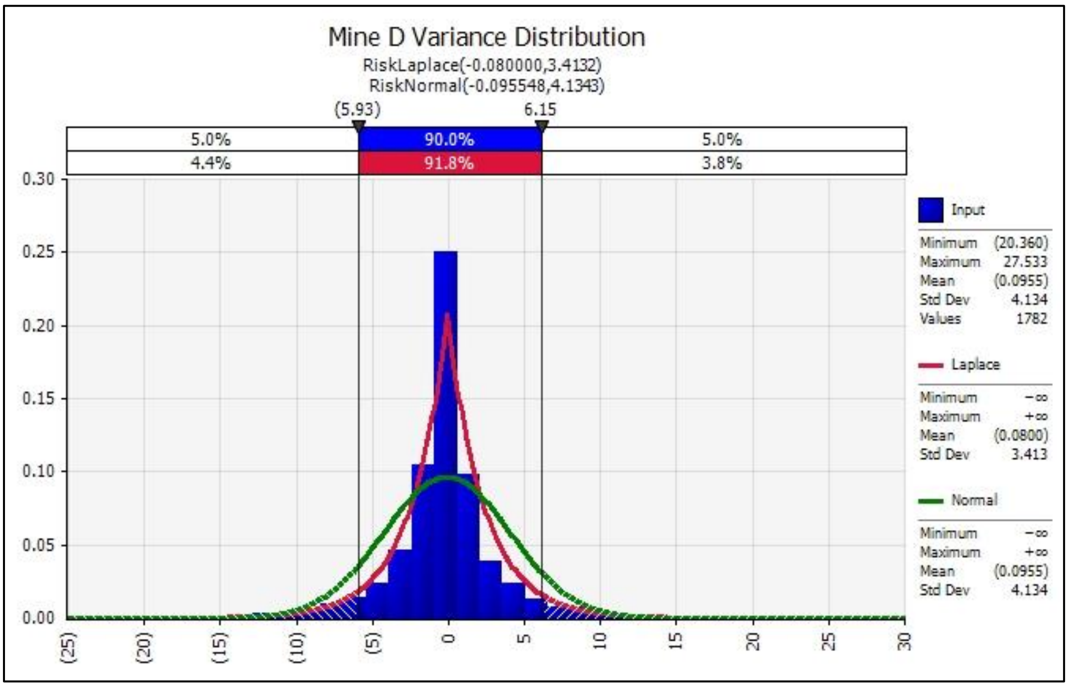

Figure 8-8. Mine D variance distribution.

It is clear from the figures that the Laplace distribution curve for the variation has a far higher kurtosis than the normal distribution curve in all four examples. They also show that Mine A, B, and C are over-estimated by 0.8, 0.4 and 1.0 g/t, respectively. Only Mine D has an overall variation of less than 0.1 g/t. This confirms the observations made in Figure 8-4, where only Mine D's best-fit line has a slope close to 1.0.

Over or under-estimation is often reflected in the block factor value, with 100% indicating no bias. These block factors were found to be 94,3%, 93,2%, 92,4% and 99.0%, respectively for the four mines. This overestimation of the block grades is very significant. It means many blocks are being identified as ore where they are sub-economic and should not be mined. If the over-estimation is carried through to the post-mining actual grade estimation for the blocks, the MRF will also be lower than expected (Minnitt, 2017). This will raise the cut-off grade. The relationship between the Laplace distribution standard deviation and the average grade of the blocks for the four mines can be determined by fitting a best-fit line. Figure

8-9 shows the relationship and the best-fit line representing this relationship for the four mines.

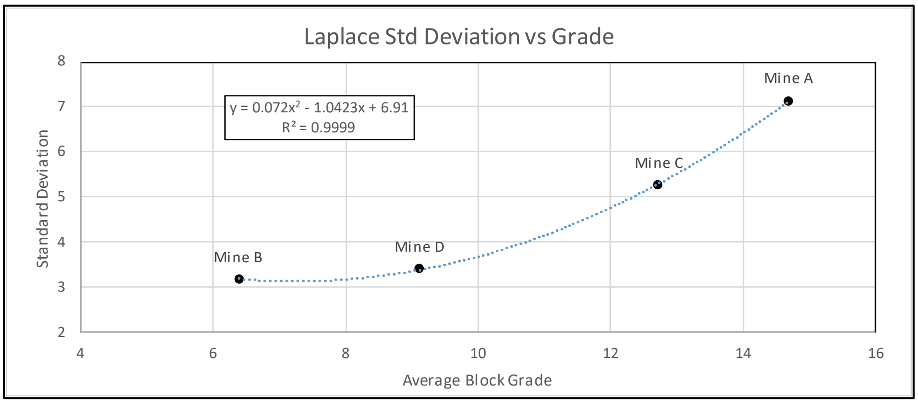

Figure 8-9. The relationship between average block grade and the Laplace distribution standard deviation.

The best-fit line indicates that a polynomial function should determine the Laplace standard deviation for determining the mines' 'actual' grades. The estimated standard deviations for the eleven mines included in this analysis are presented in Figure 8-10.

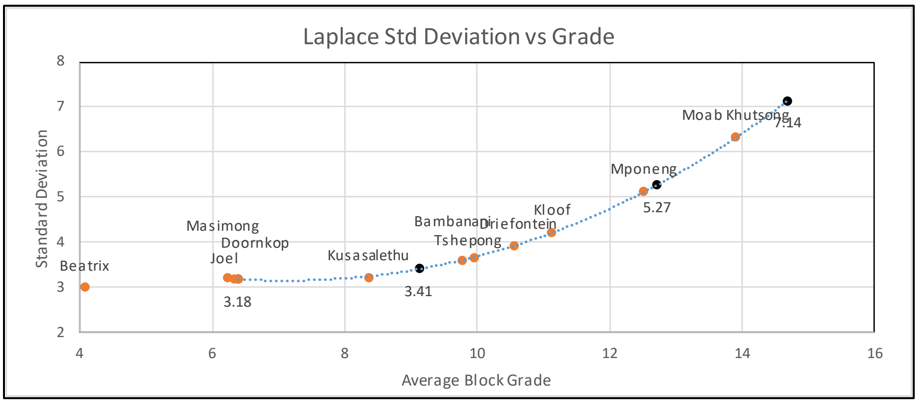

Figure 8-10. Laplace standard deviations for the mines being analysed.

8.2.4 Financial modelling

The BirchOptimiser was used for this exercise. The changes required to the basic Excel model to conduct this analysis are described in Appendix 1. The simulated block listings have an additional column added. This column is considered the ‘actual’ value. The grade assigned to this column is determined using @Risk and applying the Laplace distribution to the estimated grade. The decision to mine a block is based on the estimated grade. However, the grade used in the BirchOptimiser is the ‘actual’ grade. Figure 8-11 shows the effect of the grade estimation uncertainty on profit. This drop-in grade is primarily due to blocks with estimated grades above the financial break-even grade, yet their ‘actual’ grade is lower than the break-even grade. These blocks are diluted and are mined at a loss.

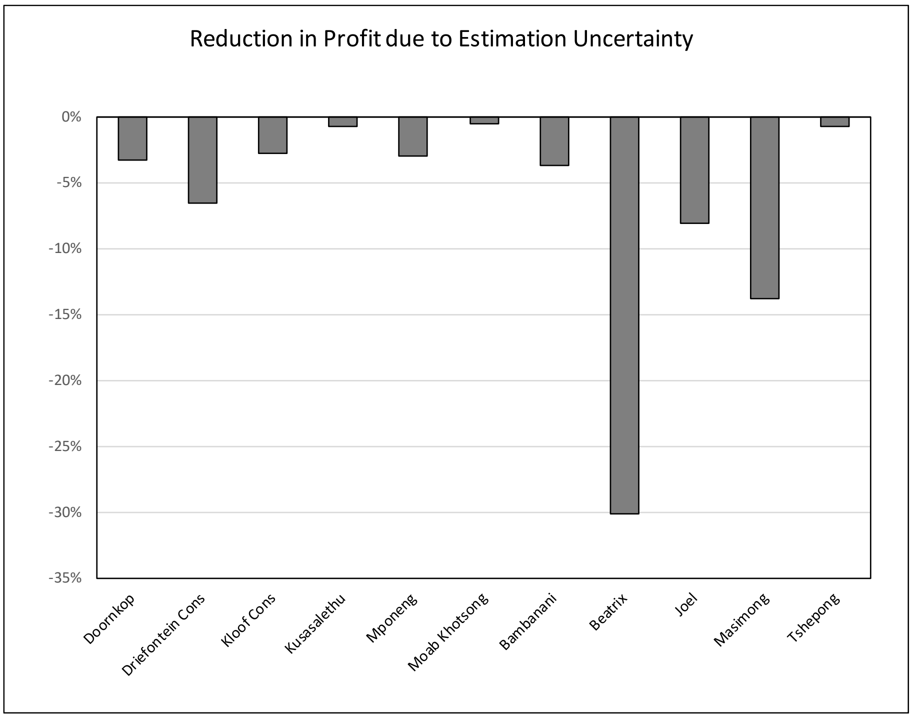

Figure 8-11. The reduction in profit when grade estimation uncertainty is considered in the financial outcome of the mine.

Minnitt (2015) identified the cost implications of poor quality sampling and grade estimations. The adverse economic effect observed with some mines in Figure 8-11 can be attributed to poor quality sampling and estimation techniques. However, no sampling campaign will result in 100% accurate values. This variance is amplified when the pre-mining grade estimations are made from values outside the blocks. For this exercise, there is no bias, and the block factors are all 100% (for every over-estimated grade, there is a corresponding under-estimated grade). The massive drop in profit at Beatrix (30%) reflects the low-grade nature of the ore body, and any drop in grade of a block would likely result in it being mined at a loss.

The BirchOptimiser (profit-optimised with variable royalty rate) is used to re-calculate the cut-off grades where the cut-off grade is applied to the estimated grades, but the financial optimisation is due to the ‘actual’ grades. The initial cut-off grades and the uncertainty optimised cut-off grades are shown in Figure 8-12.

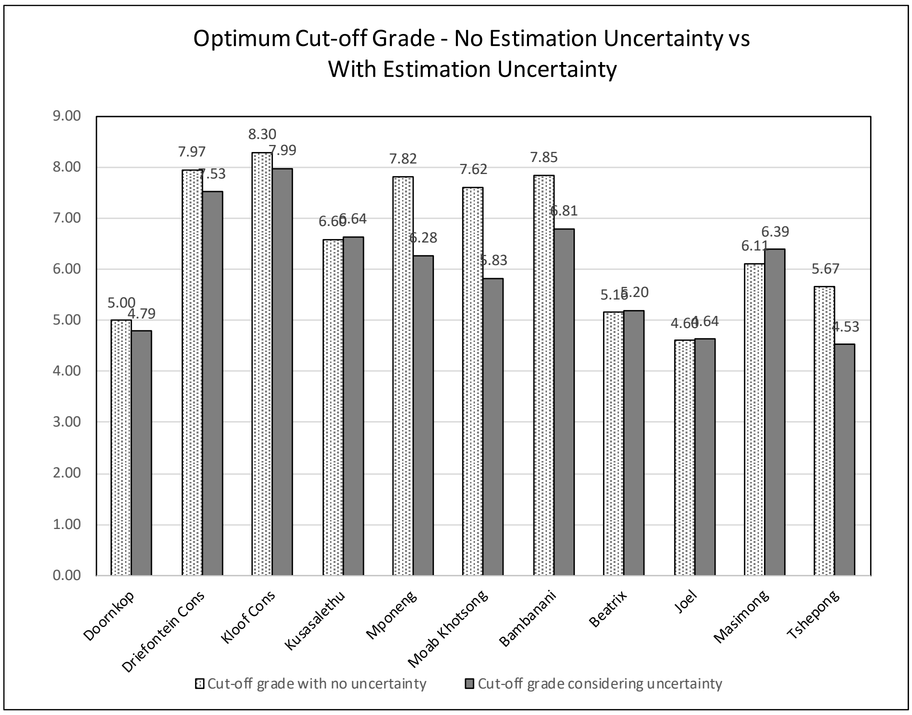

Figure 8-12. Differences in cut-off grade when estimation uncertainty is considered.

It is noted that Kusasalethu, Beatrix, Joel and Masimong mines indicate that raising the cut-off grade is preferable when optimising to reduce the profit loss due to grade estimation uncertainty. Generally, the increase is very slight (less than 0.1 g/t), except for Masimong, where a 0.3g/t increase is noted. Reducing the cut-off grade for the other mines covered in the study will increase the overall profit. This identifies that the value in the lost ore (due to a type II error) can offset the increased dilution associated with decreasing the cut-off grades. Figure 8-13 shows the profit improvement obtained by considering grade uncertainty when optimising cut-off grades.

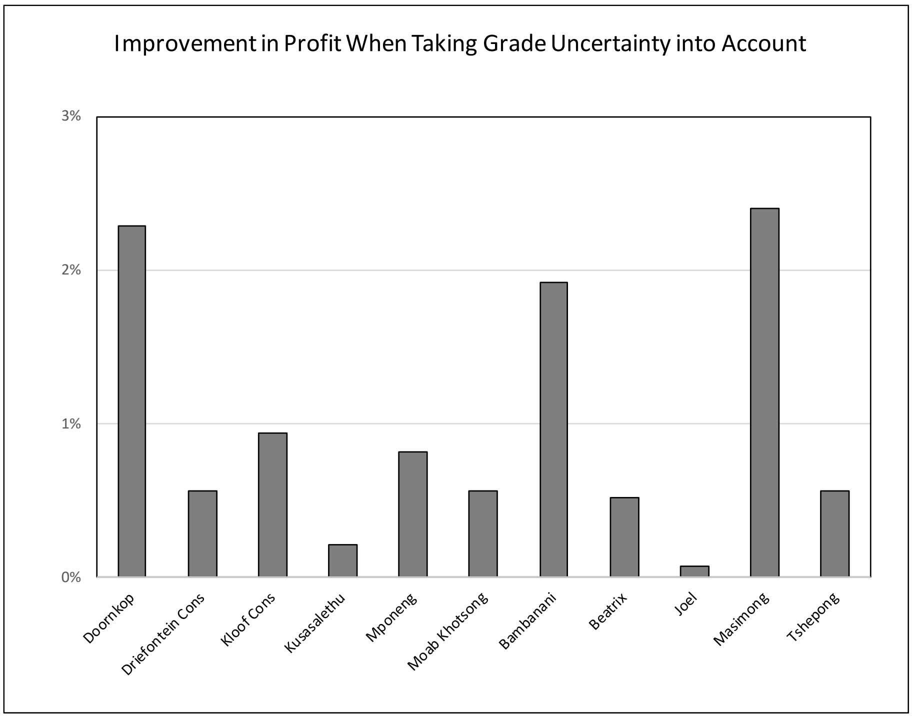

Figure 8-13. Profit improvement when considering grade estimation uncertainty.

It can be observed in Figure 8-13 that all the mines' profits can be improved by optimising the cut-off grade and considering the grade estimation uncertainty. In all cases, the revised profit figure is still below the original estimated profit when the estimated and ‘actual’ grades were considered equal. However, considering that that is an improbable scenario, mines would be over-estimating their profits even though including the MRF in the cut-off grade formula reduces this to a certain extent.

The changes in the cut-off grade alter the overall AMG and tonnes above the cut-off grade. This increases mine life for six mines, as shown in Figure 8-14. Only one of the mines (Masimong) shows a reduction in the LoM, whilst there is no change in life for the other four.

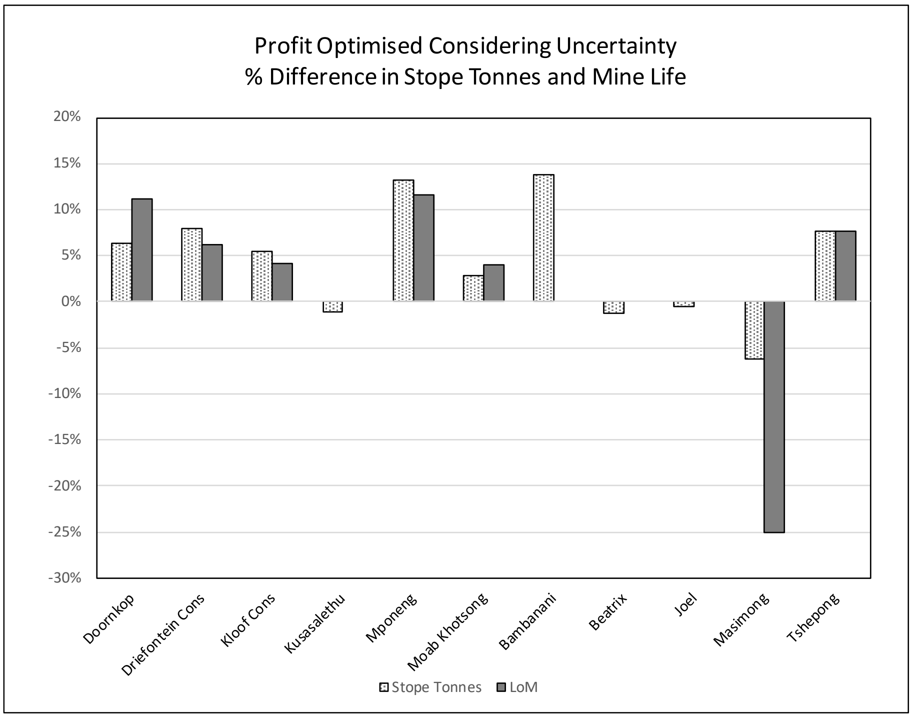

Figure 8-14. The difference in stope tonnage and mine life is considered for cut-off grade optimisation when grade estimation uncertainty.

While the profits improvements (Figure 8-13) are mostly below 2%, with only Doornkop and Masimong above 2%, the picture considering the difference in stope tonnage and mine life is very different. Figure 8-14 shows that Mponeng and Bambanani can improve their mineable stope tonnage by over 10%. Kusasalethu, Beatrix, Joel and Masimong show that increasing the cut-off grade is optimal to improve profits, with a corresponding reduction in stope tonnage (minor except for Masimong). Due to the mines' lives being rounded off to full years, only a change of at least one year is reflected on the graph. Only Masimong shows a significant reduction in LoM (although the 25% drop is due to the loss of only one year).

8.2.5 Section summary

The initial study published in 2017 (Birch, 2017) assumed a normal distribution with no bias for establishing the grade uncertainty. This study uses data obtained from four South African gold mines to establish the uncertainty associated with the estimated compared to the 'actual' grades.

The data indicates in all four cases that the distribution curve of the uncertainty of the grade estimation follows a Laplace rather than a normal curve. This “double exponential” curve displays far greater kurtosis than a normal curve with tails extending further.

In three of the four case studies, a significant bias was noted. This is displayed by block factors below 95%, indicating an over-estimation in the estimated grades. No bias was considered when estimating the ‘actual’ grades for the eleven mines included in the study. This should be corrected during the grade estimation process because bias can significantly impact value (Minnitt, 2017). It is recommended that all mines focus on their block factors and other evaluation parameters to ensure no overall bias in the block estimations. This bias could also be carried through to estimate the mined grades (the ‘actual’ grade), resulting in gold being called for, which does not exist. This apparent loss will lead to an increase in cut-off grades due to the reduction in the MRF.

The value of the lost blocks is higher than the mining losses incurred by mining more dilution by reducing the cut-off grades for seven of the eleven mines included in the study. However, every orebody has unique grade-tonnage characteristics and financial circumstances, so every mine should conduct this exercise. Financial optimisation should be conducted on all mines using their specific data. This could identify a benefit obtained by altering the cut-off grade considering grade estimation uncertainty and reducing some financial loss due to poor sampling and grade estimation techniques (Minnitt, 2017).

8.3 Multiple-Criteria Optimisation Model

8.3.1 Section introduction

The MPRDA (2002), which led to the MPRRA act being passed in 2008, states some explicit purposes in the act's preamble. These include:

- *“Acknowledging that South Africa’s mineral and petroleum resources belong to the nation and that the State is the custodian thereof;*
- *Recognising the need to promote local and rural development and the social upliftment of communities affected by mining; and*
- *Reaffirming the States commitment to reform to bring about the equitable access to South Africa’s mineral and petroleum resources.”* (The South African Government, 2002).

Considering the purposes of the act and the need for the mining industry to show commitment to these, a more holistic view regarding the optimisation of the cut-off grade is vital for mineral resource management at a national level. Reviews of the available literature regarding multiple-criteria optimisation of cut-off grades appear to focus on optimising either profit or discounted cash flow (the NPV). The impact of optimising the cut-off grade to maximise the NPV was researched during the initial stages of this research project *(Impact of discount rates on cut-off grades for narrow, tabular gold deposits* (Birch, 2016b)). This paper contrasts the profit-optimised cut-off grade to those optimised to maximise $NPV_{9\%}$ and $NPV_{12\%}$. It shows that optimising to maximise NPV severely reduces overall resource utilisation and mine life. It also highlights that the South African mining companies reviewed do not disclose their cut-off optimisation strategy in their Mineral Resource and Reserve reports. Furthermore, if they optimise NPV, the discount rate used is not disclosed.

The BirchOptimiser model developed to study the impact and management of the mineral resource royalty regime is developed as a multiple-criteria cut-off grade optimisation tool. How the BirchOptimiser is used for this approach in practice is described in Appendix 1.

8.3.2 Multiple-criteria decision analysis

Multiple-criteria decision analysis evaluates conflicting criteria and attempts to find an optimal solution. The BirchOptimiser developed for this study lends itself to performing multiple-criteria decision analysis regarding the cut-off grade optimisation considering the various stakeholder groups prevalent in the mining industry.

A multiple-criteria form of analysis is typically comprised of five components:

1. The overall goal;
2. Identification of the various options available;
3. Select the correct criteria to optimise value for the individual groups;
4. Evaluation of the criteria; and
5. Determine the weighting and the overall value (Toolshero, n.d.; Natural Resources Leadership Institute, 2011).

The overall goal

The overall goal of the exercise is to show how cut-off grades can be optimised to consider a broader definition of beneficiaries in line with the preamble of the MPRDA. To this end, the model will be run to optimise the cut-off grade to maximise various values considered beneficial to different stakeholder groups.

Once the different optimal cut-off grades are determined, a single weighted average cut-off grade is used to determine the resultant:

- Stope tonnes;
- Milled tonnes;
- LoM;
- AMG;
- Profit;
- $NPV_{12\%}$;
- TR;
- Total mining costs;
- Total royalties;
- Total income tax (gold tax); and
- Total tax contribution.

The differences between the weighted average cut-off grade and the original profit-optimised (using the variable royalty approach) are then evaluated.

Identification of the various options available

Stakeholders in the mining industry can be represented in distinct groupings, each with different requirements for the operations. For this study, four groups have been identified. These are:

- The shareholders or owners of the mine;
- The State;
- The employees; and
- The communities in which the mine operates.

However, these groups can further be split. Certain shareholders focus on the operation's overall profit, while others focus on the return on investment. The employees can also be split into those remunerated in part with profit-share or share options whilst others only receive their basic salary, perhaps with a production incentive (not related to the operation's profitability).

The State would primarily focus on the total tax contribution a mine makes. This is comprised of direct revenue from royalties and income taxes. The total taxes contribution also includes other taxes collected by the mine (including employees' income tax, social and labour plan contributions, skills development levy and dividend tax) as well as taxes borne in the form of secondary or indirect taxes (including customs duties, profit taxes from the various suppliers, exercise duties, and fuel levies) (Ralbovsky & Symons, 2010; Cawood, 2011).

Community assistance programs for people living close to mining areas are considered essential to doing business in the mining industry (Harris & Harris, 2001). The mining industry impacts local communities through three primary paths. These are:

- Employment, income and links with other sectors;
- Public spending; and
- Negative externalities from production (Chuhan-Pole, Dabalen & Land, 2017).

Mines employ local workers and procure goods and services locally. The mine is thus a boost for the nominal wages for the region and increases non-mine employment. This leads to a general increase improve local welfare and reducing poverty. The negative spillover, however, includes strains on local services (for example, health and education) due to the influx of external workers, especially during the initial construction period. Increases in housing costs can reduce the real income of some local residents (Chuhan-Pole, Dabalen & Land, 2017).

The mining industry's role in developing these communities has been recognised, and this comes through in the MPRDA. The communities would benefit from the prosperity brought to the region and the employment opportunities. They are also the beneficiaries of the social and labour plan. Corporate social responsibility is a requirement by mining companies, and they are required to report on community engagement and benefit plans as part of their annual reporting cycles. The social licence to operate cannot be underestimated (Que et al., 2019), and in South Africa, there are numerous cases of militant action by community groups aimed at mining companies. The social licence to operate is not a piece of paper required by legislation but rather a trust relationship built up through community engagement with community leaders and delivering on the expectations of those communities. If the communities only experience the negative aspects of mining (for example, competition for natural resources like water and land), they can make access to the mining areas difficult or even impossible and force mines into premature closure (Chichester, 2017).

For this study, the stakeholder groups have been simplified and classified as:

- Investors;
- Mine management;
- The State; and
- Mine employees and the community.

Select the correct criteria to optimise value for the individual groups

The simplified multiple-criteria decision analysis tool primarily aims to demonstrate how the BirchOptimiser can be adapted to determine a single cut-off grade based on a weighted average approach (Saaty & Gass, 1954; Zabihi et al., 2019). For each identified group, the main value drivers have been considered.

The investors would be focused on overall profits as well as the NPV. Since the management group primarily focuses on profit, the investors' value driver will be restricted to the NPV. Therefore, to satisfy the investors, the BirchOptimiser will be set to maximise the NPV. The discount rate of 12% has been used for other sections of this study and will also be used for this investigation.

The management and employees on profit-sharing incentive schemes will primarily focus on the overall profit. Although there could be a temptation to high-grade the operation to increase the profit for immediate gain, the sensible approach of the management team would also consider the security of a long-life operation. The value driver for this group will be the profit-optimised cut-off grade obtained by the BirchOptimiser (with the variable royalty rate).

The State would have value drivers that overlap with the other stakeholders (long life to ensure employment and profitability to increase total tax contribution). Even the optimised NPV could be considered a value driver because dividends paid to the investors are subject to dividend taxes (currently 20%). However, the combined income tax and mineral resource royalty value, along with taxes borne and employees' income tax (total tax contribution) would be seen as a value driver unique to this stakeholder group. This combined value is thus chosen as the figure to optimise through the cut-off grade.

The primary value driver for the mine employee and the community can be considered a long LoM. Optimising the mine's life cannot just be accepted as making no profit or loss (in other words, the pay limit of the operation). Profitability is required to ensure that the mine can meet its social and labour plan obligations. This approach follows Tilton and Guzmán (2016) observation that some mines lower the cut-off grade when metal prices are high to extend the LoM. The profit expectations of the parent company are met, and the extended LoM benefits the local communities (Tilton & Guzmán, 2016). The value driver identified for this group is pre-income tax profitability. A figure of 20% has been selected for this value driver, although this value is higher than 20% for several mines, even if all the available blocks are mined. The BirchOptimiser has been set so that Solver will select a cut-off grade that results in the profit/revenue ratio used to determine the gold tax rate (the x in Equation 4) returns a value of 20%. If Solver cannot reach a value of 20%, the lowest block grade is then accepted for this value.

Evaluation of the criteria

The distributions of the cut-off grades for these four criteria are shown in Figure 8-15.

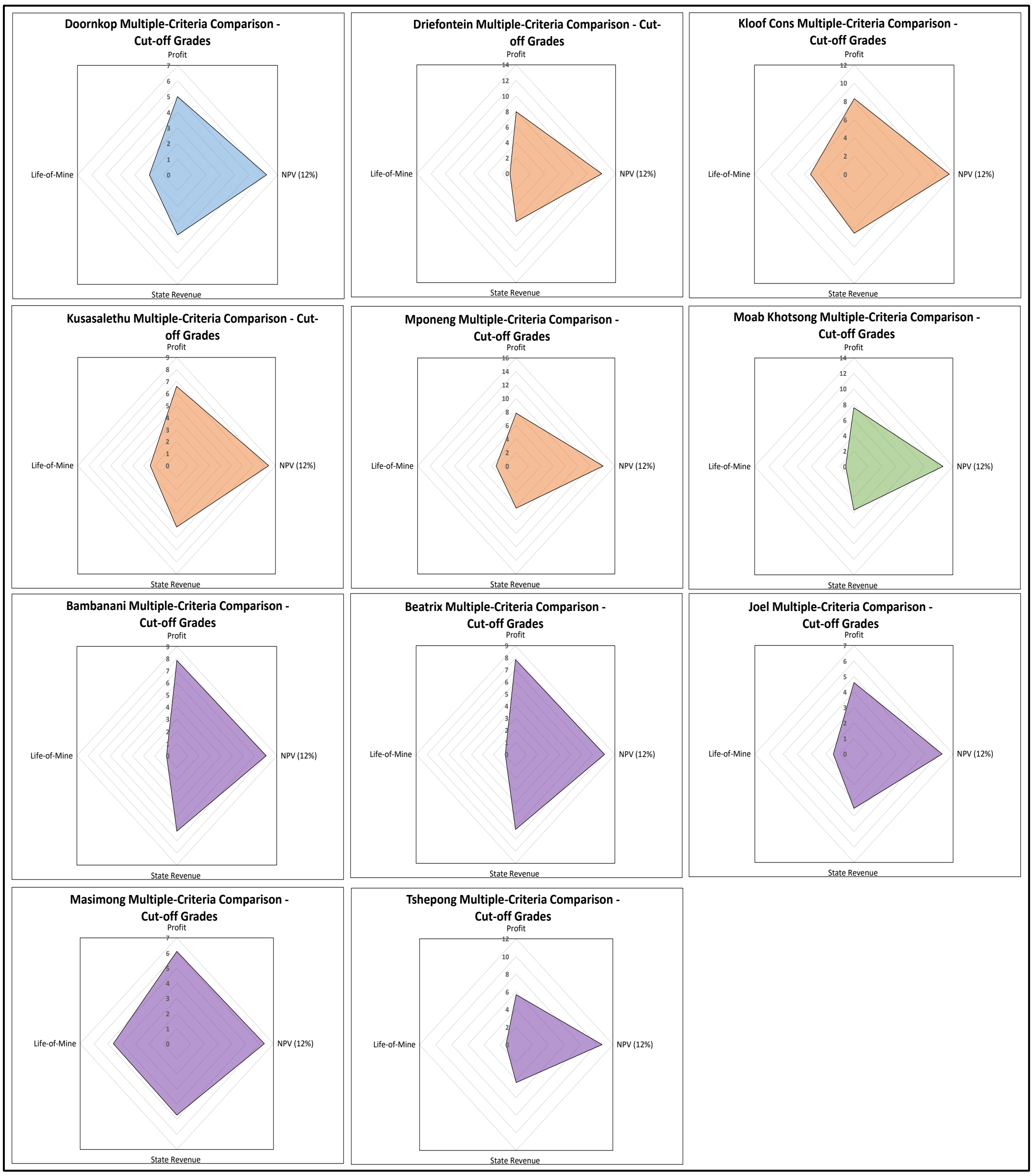

Figure 8-15. Cut-off grade distributions considering the criteria used for optimisation. Graphs are colour coded for the different regions, blue for the West Rand, orange for the West Wits, green for Klerksdorp and purple for the Free State goldfields. These graphs are shown in Appendix 3 in detail for each mine.

The BirchOptimiser determined that the cut-off grades for the eleven mines, when optimised for $NPV_{12\%}$, are the highest, whilst when optimising for the LoM, they are the lowest (except for Bambanani and Masimong, where optimising for the State results in the highest cut-off grade). These two criteria are considered the two extremes. The values determined for the cut-off grades for maximising the State's revenue and overall profit are close and lie between the other two criteria values.

In Figure 8-15, a mine with no conflict between the four criteria considered for optimisation would have a perfect square shape. There is not a single mine that shows this shape. The greater the mines' shape deviation from a perfect square, the greater the conflict between the four criteria.

Determine the weighting and the overall value

Each stakeholder group needs to be assigned a weighting to ensure their preferences are considered fair. This weighting would be unique for each mine and result from the extensive employee, community and investor engagements. However, equal weighting for each stakeholder group will be applied for this study (how altering the weighting affects the cut-off grade is demonstrated in Appendix A). The weighted average is thus:

- 25% - Investors;
- 25% - Mine management;
- 25% - The State; and
- 25% - Mine employees and the community.

Varying the weightings has a significant impact on the resultant multiple-criteria cut-off grade. This effect is demonstrated in Appendix A1-6, where an investor bias is compared to a mine employee and the community bias.

The optimised profit (with variable royalty rate) approach was identified as the preferred approach when considering the impact of the royalties on the cut-off grade. This value will be used as the base case for this multiple-criteria decision analysis. The weighted average multiple-criteria optimised cut-off grade will be compared to the base case to identify if following this approach for cut-off grade optimisation will affect the cut-off grade, stope tonnes above cut-off grade, AMG, overall profit, $NPV_{12\%}$, direct revenue to the State and LoM. Figure 8-16 shows the difference between these two cut-off grades.

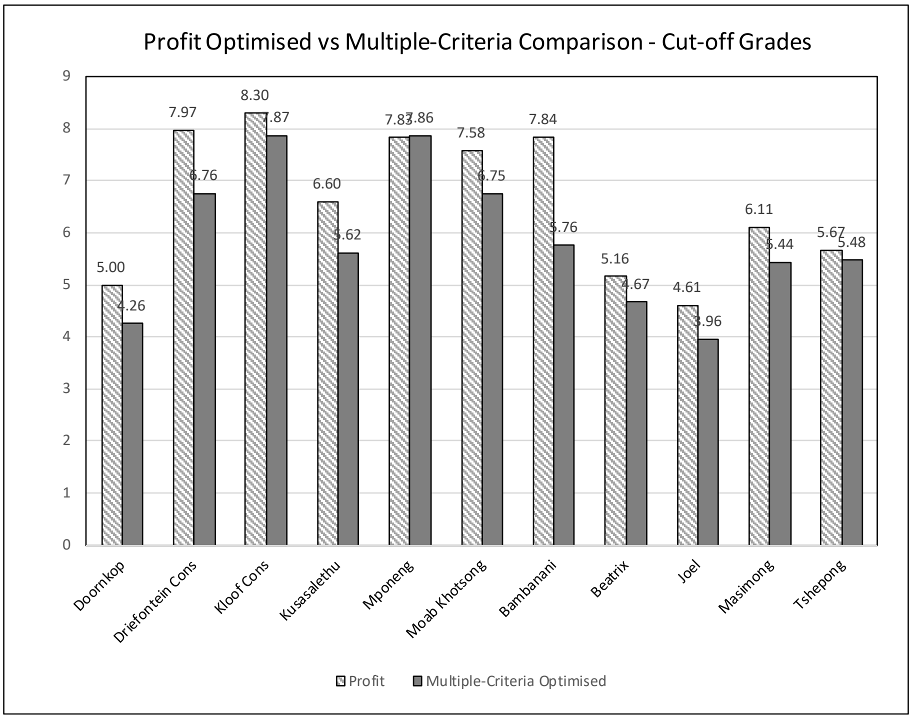

Figure 8-16. Profit and multiple-criteria optimised cut-off grades.

All the mines have multiple-criteria cut-off grades lower than the profit-optimised cut-off grade, except for Mponeng, which is slightly higher (0.4%). The difference between the weighted average multiple-criteria cut-off grade and the profit-optimised cut-off grade for most mines is less than 1.2 g/t. However, Bambanani (2.1 g/t) noted a more significant difference. The drop for Bambanani represents a relative difference of 26.5%.

The differences in stope tonnes mined and the AMG due to the change in the cut-off grade are reflected in Figure 8-17.

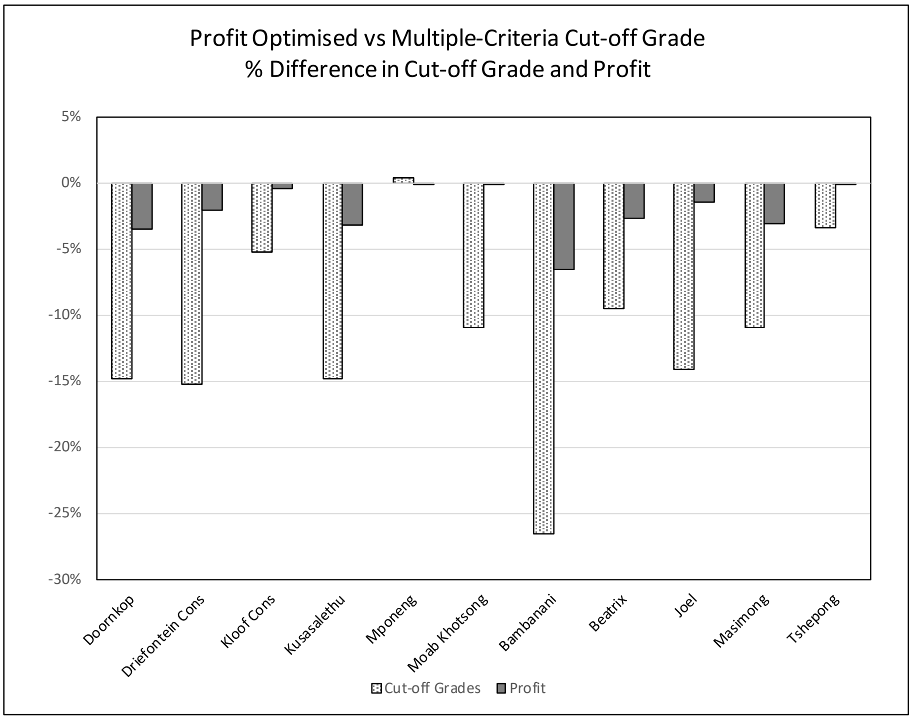

Figure 8-17. The impact of applying multiple-criteria optimised cut-off grade on the stope tonnes and AMG.

For all of the mines, there is an increase of between 1.6% and 22% noted in the stope tonnes mined when applying the multiple-criteria cut-off grade (except for Mponeng, with a 0.4% drop). There is an inverse relationship between the change in cut-off grade and the stope tonnes above this cut-off grade, where reducing the cut-off grade increases the stope tonnage available. For the AMG, there is a direct relationship between changing the cut-off grade and the effect on the AMG. The relative differences in the AMG are between 0.7% and 8.3% lower for the multiple-criteria cut-off grade compared to the profit-optimised cut-off grade (except for Mponeng, which is 0.2% higher). When considering the primary value driver for the investors, the differences in the $NPV_{12\%}$ are considered. These are shown in Figure 8-18.

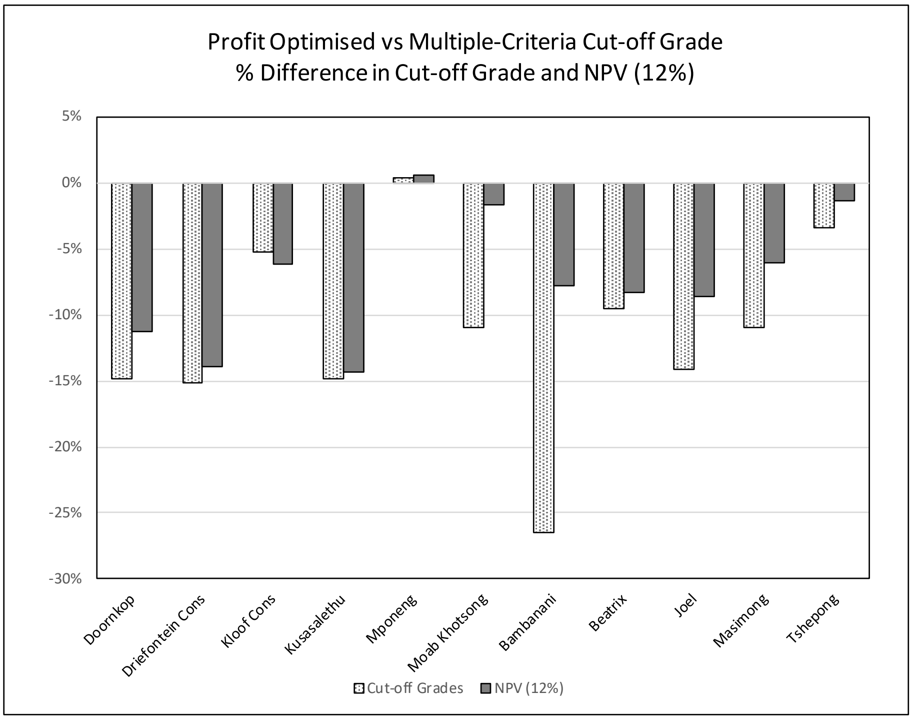

Figure 8-18. The relationship between $NPV_{12\%}$ and altering the cut-off grades.

There is a direct relationship between the cut-off grades and the $NPV_{12\%}$. Due to all the mines having multiple-criteria cut-off grades lower than those obtained for the profit-optimised cut-off grades, the resultant $NPV_{12\%}$ is also lower. This difference is between 1.3% for Tshepong and 14.3% for Kusasalethu. Mponeng is 0.6% higher.

Overall profit is considered the primary value driver for the mine management group. The impact on the overall profit from the operations due to altering the cut-off grades is displayed in Figure 8-19.

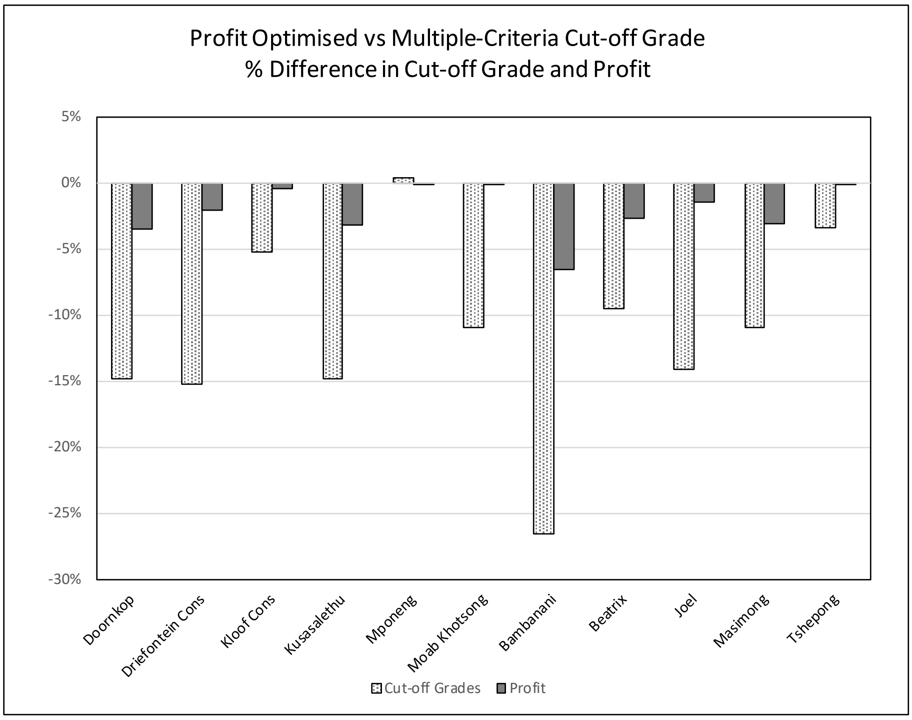

Figure 8-19. The difference in overall profit following applying a multiple-criteria cut-off grade.

As expected, all the mines show a reduced overall profit when applying the multiple-criteria cut-off grade (considering the base case for this exercise was the profit-optimised cut-off grade). The most considerable difference in profit is noted for Bambanani, where the overall profit is reduced by 6.8%. There is hardly any difference in the profit for Mponeng (0%) and Moab Khotsong (0.1%).

Figure 8-20 considers how changing the cut-off grade affects the direct revenue to the State (measured as the combination of the mineral resource royalty and income tax costs as well as employees’ income tax and taxes borne).

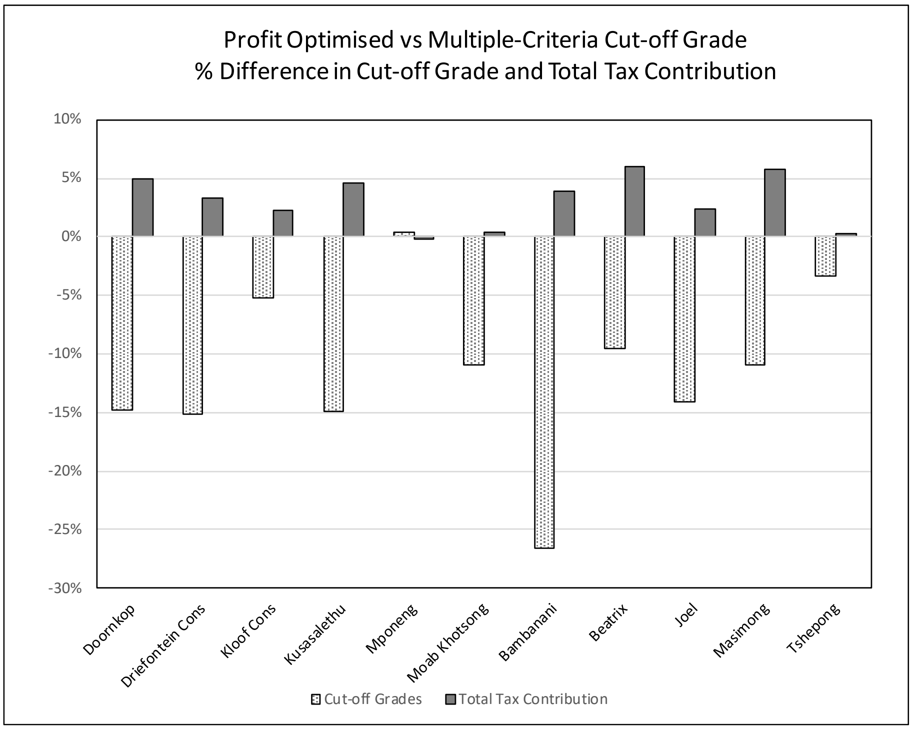

Figure 8-20. The difference in total tax revenue to the State after adopting a multiple-criteria cut-off grade.

The State would receive increased revenue for all the mines if the multi-criteria cut-off grade were applied (except Mponeng with a 0.1% decrease). The most significant increase is for Doornkop, Beatrix, and Masimong, all increasing by over 5%.

Figure 8-21 displays the difference in mine life when this value is optimised to benefit the mine employees and the communities in which the mine operates.

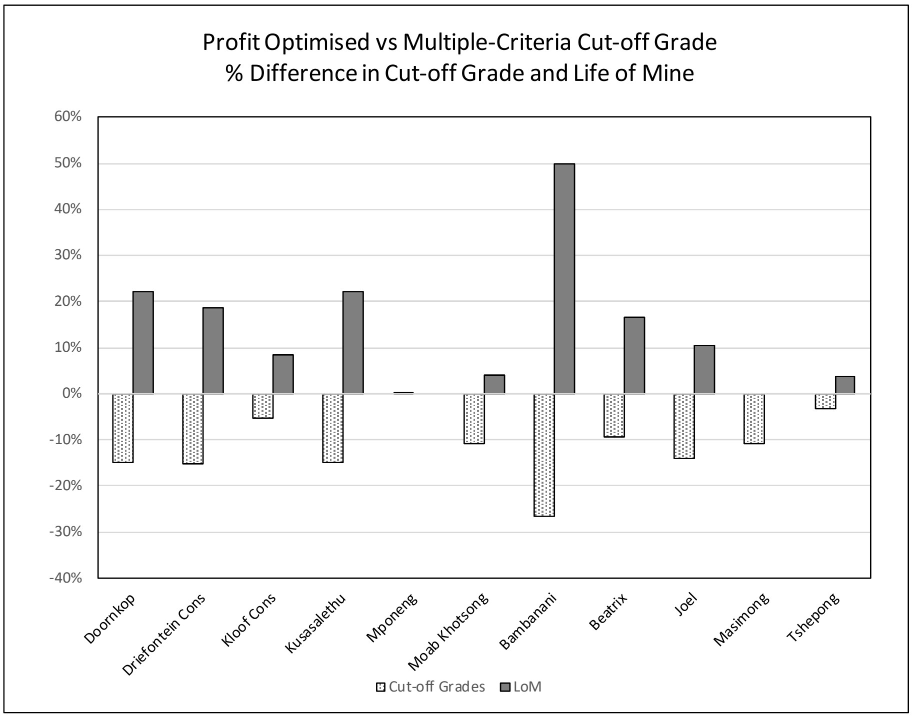

Figure 8-21. The difference in mine life following multiple-criteria optimisation of the cut-off grades.

For this analysis, the LoM data has been rounded off to the nearest whole year. It can be observed that following the weighted average multiple-criteria approach, the lives of all mines have been extended by up by 50% in the case of Bambanani, which is only an additional one year on a very short life. More significant are the increases at Doornkop (22%), Driefontein Cons (19%), and Kusasalethu (22%).

The complete results for the different mines are available in Appendix 3 (A-K).

8.3.3 Section summary

This analysis has demonstrated how the BirchOptimiser developed for this study can be applied in multiple-criteria decision-making and resolve conflicts that arise when considering the various stakeholders in the mining industry. For each mine, the effect of applying a weighted average multiple-criteria cut-off grade is different when considering the various parameters reviewed. Such an approach's real value is not merely determining a slightly altered cut-off grade. The benefit lies in the engagement process with the various stakeholders and in showing that the company is willing to consider their needs.

The company's financial obligations to its shareholders and the State can be demonstrated using the basic break-even grade calculation through mining stakeholder dialogues. This break-even grade could then be the foundation on which the multiple-criteria optimised cut-off grade is determined with input from the stakeholder groups. Workshops and roadshows would be required to identify the specific value drivers for each stakeholder group. Negotiations around a common table with representatives of these stakeholder groups would determine the weighting of each value driver and, ultimately, the weighted average multiple-criteria cut-off grade. This approach to determining the cut-off grade could add immeasurable value to operating social licences.

8.4 Chapter Summary

This chapter has presented two new approaches to optimising cut-off grades using the financial optimiser model's flexibility developed for this study.

The BirchOptimiser allows the block to be included in the mine plan based on the estimated grade, whilst the ‘actual’ grade is used in the cash flow to determine the resultant revenue from the block. This flexibility has shown that reducing the cut-off grade will reduce the value lost due to grade estimation uncertainty on most of the mines reviewed.

It has been shown through the previous chapters in the study that optimising to maximise the NPV increases the cut-off grade, reducing the mine life and the amount of ore extracted from the mineral resource. The flexibility of the

BirchOptimiser allows a multiple-criteria approach to cut-off grade optimisation. While other multiple-criteria optimisers are noted in the literature, they focus on balancing multiple inputs to maximise profit or NPV. The approach developed in this study balances various measures of value, considering the needs of the different stakeholders found in the mining industry.

The following chapter is the conclusion and makes recommendations for further research.

9 CONCLUSION AND RECOMMENDATIONS

9.1 Introduction

The cut-off grade identifies the boundary between ore and waste and fundamentally affects the classifying and managing of Mineral Resources and Reserves. This value determines what portion of the available Mineral Resource can be economically mined and the AMG of this ore. This value is critical to the mine planning process and is usually determined as part of the annual mine planning cycle. It is thus one of the critical components to determine before publishing the annual Mineral Reserve. Altering the cut-off grade affects the overall mine life and the flow of revenue from the operation. This value can be optimised to maximise the profit from a mine.

This research project was conceived on the questions raised by introducing the Mineral Resources Royalty in 2010 and how these costs must be considered when determining the cut-off grade. In South Africa, the gold mines pay income tax, where the gold tax formula establishes the rate. All other mining ventures pay income tax at a fixed rate.

The mineral resource royalty and the gold tax formula’s rates vary following the profitability of the mine. The nature of the mineral resource royalty formulas differs from most other significant precious metal producing countries that apply fixed rates (with the base differing between them). The conventional approach does not include profit-based taxes as costs when determining the cut-off grade. However, the royalty costs are included when applied to total revenue or volume produced. There is no clarity in the available literature regarding the hybrid approach to determining the royalty rates and subsequent costs, as in South Africa. This is further complicated by the mineral resource royalties being considered a tax-deductible cost (affecting the profitability ratio) when calculating the gold tax rate. South African gold mines are subject to a unique combination of direct taxes not noted among the other significant gold-producing countries.

Profitability is thus an important consideration when establishing the cut-off grade. Opportunities present themselves to increase the overall profit when reduced profitability ratios decrease royalty and tax rates.

An Excel-based financial optimiser has been developed that allows various approaches to dealing with the mineral resource royalty cost to be explored. This BirchOptimiser uses the simple and freely available Excel mixed-integer linear programming Solver function.

9.2 Summary of Chapters

This thesis has presented nine chapters that cover the following:

- The introduction chapter gave background to the South African mineral resource royalty and how it applied to the Witwatersrand gold mines. The problem statement indicated that the industry standard is to include these costs in establishing the cut-off grade, which is affecting the mines' lives.
- Chapter 2 overviewed the various mineral resource royalties' forms and the taxes applicable to the South African mining industry.
- Chapter 3 reviewed the mineral resource royalties for the ten most significant gold-producing countries. When measured as a percentage of total costs, South Africa has the lowest. However, this is not just a function of the royalty cost itself. It also shows that the South African gold mines are the highest cost of any significant gold-producing country, so the royalty costs are proportionally lower. Furthermore, the marginal nature of the mines due to the high costs makes the South African mines more sensitive to additional costs.
- The fourth chapter reviews the various approaches to determining the cut-off grade and is considered while developing the optimiser model used in this study.
- Chapter 5 outlines the determination of break-even cut-off grades and the various formulae used to develop a financial cut-off grade

optimiser (the BirchOptimiser). This cut-off grade optimiser uses data readily available on narrow, tabular gold mines to determine the cut-off grade to optimise either profit or NPV.

- Chapter 6 is an overview of the Witwatersrand goldfields, which have active mines included in this study. The cost and production estimates for the eleven mines included in this study are presented, and the Measured and Indicated Mineral Resources are tabulated.
- The following chapter presents the results of the mineral resource royalty cost approach study. The best approach for determining the cut-off grade is to either ignore the cut-off grade or only consider the 0.5% rate as a cost when optimising for profit. The findings demonstrate how reducing the cut-off grade benefits LoM, Mineral Resource utilisation and revenue for the State. The study also demonstrated how optimising for NPV, the increase in cut-off grade severely reduces mine life.
- Chapter 8 presents two new approaches to optimising cut-off grades. The first approach considers how grade estimation uncertainty reduces the value from the mine. The approach considers how the cut-off grade can be adjusted to minimise this loss. In eight of the eleven mines analysed, the optimal approach is to reduce the cut-off grade to minimise the lost ore, even though it increases dilution. The second new approach is to apply a multiple-criteria cut-off grade approach. This approach considers the interests of the various stakeholders in the mining industry and how a weighted-average cut-off grade can be determined.
- The final chapter concludes the study and makes recommendations for further research.
- Three appendices are included in this thesis. Appendix 1 describes the construction and use of the BirchOptimiser developed for this study. Appendices 2 and 3 present the results of the mineral resource royalty cost optimisation study and the multiple-criteria cut-off grade optimisation approach, respectively.

9.3 Research Observations

9.3.1 Initial and complimentary studies

This thesis represents the final research portion, which commenced in 2015. Several questions have been considered, and these have been published separately as journal and conference articles. These include:

- The initial mineral resource royalty impact study;
- Optimisation of profit or NPV;
- Cut-off grade optimisation approaches commonly found in Southern Africa;
- Impact of the mining block sizes; and
- Managing grade estimation uncertainties.

Initial mineral resource royalty study

This research commenced with an initial study that explored the impact of the mineral resource royalty (*The impact of South African mineral resource royalty on cut-off grades for narrow, tabular Witwatersrand gold deposits*)(Birch, 2016a). It was noted that the expected royalty cost was estimated based on the expected profitability of the gold mining companies reviewed. This value was included in the costs used to determine the cut-off grade.

The initial study compared the cut-off grades obtained by including and excluding the mineral resource royalty (the cost determined by the general approach followed by the seven mines reviewed). It was established that the added costs of the mineral resource royalty increased the cut-off grade, thereby reducing the mineable tonnage from the Mineral Resource. This was shown to have a detrimental effect on the mines' lives. Furthermore, in some cases, direct revenues (royalties and income tax) to the State were reduced after introducing the mineral resource royalty due to the reduction in mining. The indirect revenue streams to the State through the various secondary sources would also be severely impacted.

This initial study identified that various alternative approaches to the mineral resource royalty costs could be considered to identify which approach was optimal. These ranged from excluding the costs, using the minimum rate (0.5%), the maximum rate (5% in the case of refined products like gold) or an estimated rate. There was also the consideration that a variable rate (where a financial optimised determines the rate) might be optimal where reduced profitability and the subsequent decreased royalty and income tax rates result in increased revenue and profits.

Profit vs net present value optimisation

During the initial study (Birch, 2016a), it was identified that optimising for NPV as opposed to profit significantly impacts the cut-off grades. This was explored further and published as a journal article in 2016 (*Impact of discount rates on cut-off grades for narrow tabular gold deposits*). The findings from that study have shown a need for a more holistic consideration of the mining industry stakeholders when determining the cut-off grades (Birch, 2016b).

Cut-off grade optimisation approaches

A review of cut-off grade optimisation approaches was undertaken utilising student assignments. It was shown that cut-off grade optimisation is very rudimentary on most Southern African mining projects (across various countries and commodities). It is more developed amongst the open-pit operations, where some have implemented tools like the Whittle Optimiser and Lane's Algorithm. Most underground operations determine the basic break-even grade and apply that as the cut-off grade. The findings of this research were published in 2018 (*Review of cut-off grade optimisation from Southern African mines. Student assignment based observations*) (Birch, 2018).

Block size considerations

The Mineral Resource block listing forms the foundation on which the BirchOptimiser has been developed. An approach was developed using the published Mineral Resources (Measured and Indicated) to create simulated block listings. The published grade-tonnage curve is used to determine the grade distribution profile, which is then matched for the simulated block listing using @Risk. The number of blocks is selected to match the tonnages in the published Mineral Reserve with the dimensions selected to match the published dimensions (area and SW).

However, this has raised questions regarding the sizes of the blocks used to publish the Mineral Resource. It has been determined that these blocks are smaller than what would be considered the SMU for deep and ultra-deep mining. *Optimisation of mining block size for narrow, tabular gold deposits* (Birch, 2019) investigated this further and determined that the mines would not match the published AMGs considering the dilution associated with larger SMUs than used for the Mineral Resource declaration.

This discrepancy is not considered critical for a study of this nature, which is predominantly comparative. However, the data presented in this study would not match the various mines published Mineral Reserves even though the same fundamental modifying factors are used in the BirchOptimiser. Investors would expect to follow a Mineral Resource reflected in the grade-tonnage curve to the Mineral Reserve by applying a cut-off grade (to determine the total mineable tonnes and the AMG) and the other published modifying factors. The dilution effect of the larger SMUs found in the South African gold mines makes this impossible.

Grade estimation uncertainties

One of the assumptions of applying a cut-off grade is that the estimated and the ‘actual’ grades are the same. Mines estimated the block grades ahead of the mining face by applying appropriate geostatistical methods. The 'actual' grades are also estimates but are established through sampling within the mining block. Because the sampling occurs during mining, the values represent a better estimate of the actual block value. However, this is still an estimated grade, and any bias in the sampling or estimation techniques will still be present. In the case of the over-estimation, as noted in the case study with three of the four mines, this bias will reflect in a lower MCF and subsequent MRF and be considered when calculating the cut-off grade. Even if the block factor is 100%, there is still uncertainty in the estimated grades. All this indicates a corresponding under-estimated block grade for every over-estimated block grade.

Sampling and grade estimation will always be subject to a certain degree of uncertainty. This uncertainty affects the flow of value from a mine through two distinctive errors. If the estimated grade is above the cut-off grade, but the 'actual' grade is below the break-even grade, the block is mined at a loss. This error will result in dilution. The block is never mined if the estimated grade is below the cut-off grade. If the 'actual' grade is above the break-even grade, this block could have contributed to the profit of the mine. This is considered lost ore.

An initial study (*Optimization of cut-off grades considering grade uncertainty in narrow, tabular gold deposits* (Birch, 2017)) considered how adjusting the cut-off grade to minimise either the dilution or the lost ore could recover lost profits from these two forms of error. It assumed the uncertainty would be a normal distribution, and the degree of uncertainty was varied by adjusting the cut-off grade. There was an indication that reducing the cut-off grade to reduce the lost ore would be financially beneficial. Data has been obtained from four gold mines to determine the actual distribution form of the uncertainty and the standard deviations. It is shown that these are Laplace distributions, and there is a relationship between the overall Mineral Resource grade and the standard deviation. These uncertainties have been modelled to create simulated 'actual' values from the estimated values.

Financially modelling using the BirchOptimiser developed for this study shows that seven of the eleven mines are preferred to reduce the cut-off grades. This overall result confirms the published findings from the initial investigation.

9.3.2 Key findings and observations for understanding the impact of mineral resource royalties

South African gold mining companies are uniquely charged income tax and royalties. The mineral resource royalty introduced in 2010 is a hybrid *ad valorem* model with the profitability of an operation determining the rate (which is then applied to the total revenue derived from mineral sales). The gold tax formula is used to determine the income tax rate and uses the profitability of an operation in determining the rate. These unique approaches have led to the question, “if decreasing the profitability of an operation by lowering the cut-off grade will lead to higher profits?” The BirchOptimiser developed for this study has been used to identify the optimal approach when considering the mineral resource royalty costs is ignoring them when determining the cut-off grade.

Furthermore, the BirchOptimiser has identified that additional profit gains can be made by reducing the cut-off grade further. The reduced profitability results in lower royalty and income tax rates. Whilst the actual differences in profits obtained from the study are minor (0.5% when compared to the break-even base case), significant gains in stope tonnes above cut-off grade and resource tonnage utilisation (9%), total revenue (5.9%) and total tax contribution (conservatively estimated to be 2.75%) can be achieved. The higher resource utilisation would lower the required development needed to maintain the mines target output, leading to lower AISC. This, in turn, will allow further reductions in the cut-off grade and increase profits.

9.4 Research Contributions

9.4.1 Development of the BirchOptimiser

This study has resulted in a robust financial optimiser that can easily be implemented for any narrow, tabular precious metal mine following the financial cut-off grade approach. This BirchOptimiser is built on the mines' block listings. A cash flow then determines the overall profit and NPV considering the various modifying factors (including the metal price, mining costs, the ratio of stope tonnes to milled tonnes and the MRF). The tonnes above the cut-off grade and the AMG change as the cut-off grade is altered. This BirchOptimiser is considered unique because the mineral resource royalty and the gold tax rates adjust per the profitability. The Excel Solver function is then applied to optimise the value of either the profit, NPV or any other value or combination of values as required.

9.4.2 Development of a multiple-criteria cut-off grade optimisation approach

The flexibility of the BirchOptimiser lends itself to being developed as a multiple-criteria cut-off grade optimiser. An approach has been developed where value optimisation takes a more holistic view of the needs of a broader base of mining stakeholders. The case presented in this study includes the investors, mine management, State, mine employees and local communities.

However, the actual value of the multiple-criteria optimisation approach is not to determine a slightly different cut-off grade. Identifying the key value drivers of the various stakeholder groups will require the mines to engage with these groups. There would be negotiations around weighting these value drivers considering the conflicting needs between the groups. This process will create dialogue and a broader understanding of each stakeholder group's expected benefits from the ore body. It will also develop the understanding amongst these groups regarding the finite nature of the ore body and that if the demands are too high, the mine will close prematurely. This approach will go a long way in obtaining the social licence to operate, which is vital in the current mining industry.

9.4.3 Development of an approach to consider grade estimation uncertainty in cut-off grade optimisation

The block listing underlying the BirchOptimiser has been modified to include simulated 'actual' values. The model selects the blocks to be mined using the estimated grades, but the financial optimisation takes place based on the financial returns of these 'actual' values. This approach shows that lowering the cut-off grade is, in most cases, the optimal approach. It benefits the mines because it allows more ore to be mined, extending the life and overall resource utilisation. The approach also demonstrates how much value can be lost through poor quality sampling and grade estimation.

9.4.4 The optimal approach to mitigate the impact of the mineral resource royalty costs on cut-off grades

It has been determined that the optimal approach is to use the variable royalty rate. However, the resultant cut-off grade is similar to excluding the mineral resource royalty cost or using the minimal rate in the calculation. If this is the approach adopted by the mine, the royalty costs have no impact on the cut-off grade. This finding is significant because the nature of a mineral royalty is regressive (i.e., based on mineral sales), but the sliding of the rate is influenced by annual profitability, which makes the South African royalty progressive. Calculating the South African mineral resource royalty can also be considered 'neutral' because it does not alter the fundamental mine planning regarding the ore-waste boundary and resultant mineable tonnes and AMG.

The BirchOptimiser has been used to demonstrate the optimal approach when considering the costs associated with the mineral resource royalty. It is shown that these costs should be ignored or only the minimum rate be applied. The approach also shows how the mineral resource royalty and gold tax interact and that lowering the profitability of the mine increases overall profit. This research's contribution is that South African gold mines can lower their cut-off grades significantly compared to the cut-off grades obtained with the current approach (estimating the rate and the resultant cost and including this in the cut-off grade calculation). The mineral resource royalty formula was developed not to influence mineable resources and ensure maximum resource utilisation. The approach from this study shows that the formula does not need to affect the cut-off grade and is achieving its goal. South Africa has a massive problem with unemployment, and any job losses in the mining industry are likely not to be replaced (Statistics South Africa, 2021). It is considered critical that job preservation be considered when making optimisation decisions.

9.5 Research Limitations

This research has relied predominantly on the published Measured and Indicated Mineral Resources, grade-tonnage curves and modifying factors. The financial assumptions are also based on the data obtained in the public domain. It is noted that although the Mineral Resource data are split between the various operations, the grade-tonnage curves are for the combined Mineral Resource. The financial and modifying factors are also combined for the entire operation.

Cut-off grade optimisation can be applied separately to each shaft, ore body, and mining area. This data is available on the operations but not in the public domain. However, this study was focused on developing a methodology and demonstrating the benefits of adopting the various approaches. Thus, the limitations of the available data in the public domain are not considered critical for this study to achieve the intended results. The operations can adopt this methodology to develop their cut-off grade optimising approaches using all the information they have at their disposal.

9.6 Recommendations for Future Research Work

9.6.1 Understanding how changes to the gold tax will affect gold mine cut-off grades

South African gold mines pay income tax on a profitability-based sliding scale. While this talks to the “ability to pay” concept, it is out of line with all other mining activities taxed at the corporate tax rate (not considered neutral). The current formula allows gold mines tax relief where the margin is below 5% (the tax tunnel) and rises to 34% when the mine is highly profitable. This form of taxation was introduced initially to encourage gold mining investment.

On August 13, 2015, the Davis Tax Committee committee's first interim report on mining was posted for public comment, proposing no changes to the gold tax formula currently used for gold mines (Deloitte, 2015). This proposal was to protect jobs and keep the gold mines operating, considering the marginal nature of many mines (Deloitte, 2015). Although the committee has recommended retaining the gold mining formula for existing gold mines, it has proposed that new gold mines be subject to the same tax rates as other mining projects to ensure neutrality in the mining sector (Deloitte, 2015).

Lilford (2017) identified that changes in tax regimes could be very detrimental to the mining industry if the ore body and the impact on cut-off grades are not considered. The study by Lilford (2017), considering the proposed introduction of mining royalties in Australia, emphasised the importance of understanding how these changes affect cut-off grades. He stated, *“Policy-makers and legislators, typically representing a government body, are quick to impose royalties and other measures to secure income from natural resources operations”*. He identified that these same regulators seldom question the impact of such additional costs beyond profit-based taxes on the actual operations regarding economic life (Lilford, 2017).

Considering the criticisms raised by Lilford, the impact of changing the current gold tax levied on the South African gold mines to the constant income tax rate levied on all other mining operations should be investigated. This will determine if the gold mines can afford to be taxed at a flat rate or if the impact on the cut-off grade would be significant and result in less utilisation of the Mineral Resources.

9.6.2 Securing the future of the mining industry

"*Recognising the need to promote local and rural development and the social upliftment of communities affected by mining"* is stated in the preamble to the MPRDA (The South African Government, 2002). The MPRRA has been introduced to distribute some of the financial benefits from the mineral resources back to the State and, by extension, the country's citizens. The ANC SIMS document identifies no boundary applicable to the benefit of the mineral resource royalty, and all the citizens are affected by mining (ANC, 2012). The local communities in the mining areas will thus not receive any preferential benefits from the mineral resource royalty revenues. It is up to the mining companies to show they are considering the needs of the local communities through other mechanisms. One of these is ensuring the mine utilises the mineral resources optimally in a way that does not just benefit the shareholders.

When this is translated into the cut-off grade approach, there should be a consideration of how the resource can be optimally mined to show adherence to the tenets of the MPRDA. It is clear from the study that optimising to maximise the NPV increases the cut-off grades and reduces mine life significantly. A proposal and methodology for a multiple-criteria cut-off grade approach have been made, with the benefit for the mine being the mining stakeholder dialogues that are part of the process. This would go towards the social licence to operate.

However, mines are not obliged to consider local communities' needs when determining their cut-off grade approach. No legislation forces mines to consider extending the mine life through their cut-off grade optimisation approaches. There have been times in the country's history when the government has been far more prescriptive in how the mines establish the ore-waste boundaries. It is certainly not to the benefit of the mines to return to such a model, so they should undoubtedly invite the State to be part of the stakeholder negotiations to show that the principles of the MPRDA are being taken into consideration whilst determining the cut-off grade approach.

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APPENDIX 1 BIRCHOPTIMISER

A1.1 Introduction

The BirchOptimiser has been developed to determine the optimal approach regarding the mineral resource royalty costs when determining the cut-off grade for narrow, tabular gold deposits in South Africa. The Excel model links the block model created to declare a mineral resource to a cash flow model. The cut-off grade controls the AMG and the tonnes above the cut-off grade that are available for the cash flow. The Excel Solver function is used to optimise the resultant profit or NPV.

For the initial study of this thesis, this approach was used to compare various scenarios of how the mineral reserve royalties can be considered when determining the cut-off grade. The BirchOptimiser has also demonstrated that a more flexible approach to cut-off grade optimisation is possible. The optimiser has been used to develop a method to optimise the cut-off grade considering grade estimation uncertainties. Furthermore, a multiple-criteria cut-off grade approach has been developed where different stakeholder group preferences are considered. The optimiser is set to optimise not just on profit or NPV as all the current cut-off grade approaches do. The direct revenue to the state and a long mine life is also demonstrated. The benefit of this approach is not in determining a different cut-off grade but rather in the dialogues that would take place with the various stakeholder groups. This would demonstrate a more holistic view to value and allow each stakeholder group to define which approach to cut-off grade optimisation would benefit their particular needs. Finally, negotiations around the weighting factors would require robust negotiations and compromises before the final cut-off grade is determined.

A1.2 Structure of the BirchOptimiser

The layout for the BirchOptimiser used for this study is laid out in a series of tables spread across two Excel sheets (the Blocklist and Cashflow Sheets). The presentation of the tables in this description has been selected to follow the logic of the optimisation process. The figures presented are from the Kusasalethu Mine on the West Wits Line of the Witwatersrand. Figure A-1 shows the layout of the tables within the BirchOptimiser.

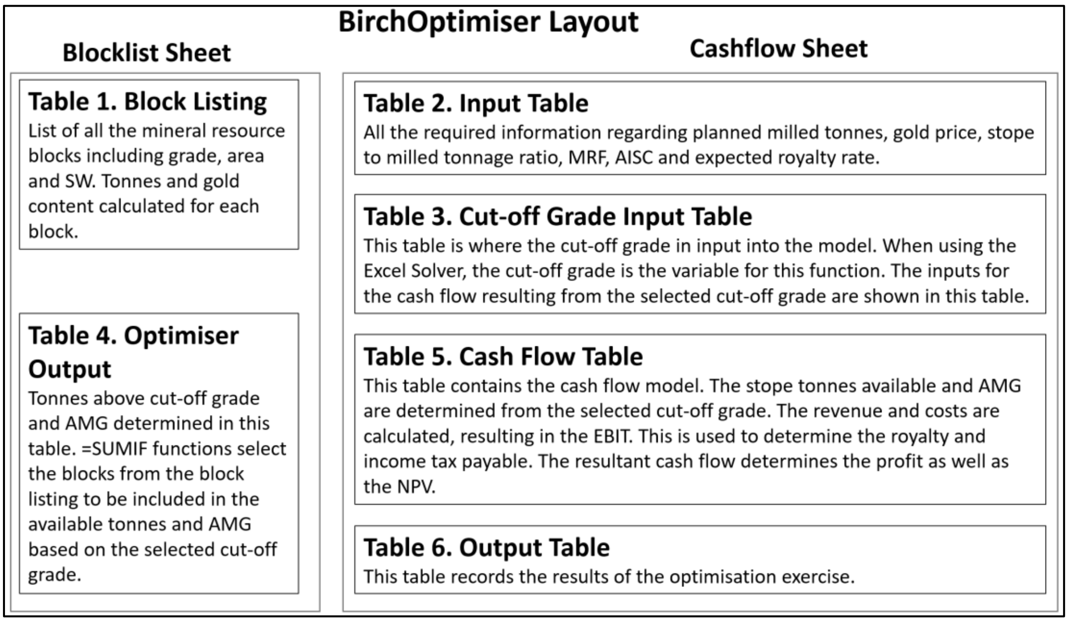

Figure A-1. The layout of the BirchOptimiser.

A third Excel sheet (GT Curve Sheet) is included in the BirchOptimiser Excel file, which generates the grade-tonnage curve for the investigated mine.

Table 1. Block listing (Blocklist Sheet)

The block listings used for this thesis have been simulated from the published mineral resources and reserves for the various gold mines reviewed. Typically, the block listings would be obtained from the mines, forming the basis of the Mineral Resources and Reserves. Not all the columns in the mines’ block listing are required, and some editing of the figures is necessary. The grade in the mines’ block listing is generally over the channel width, and cmg/t is used in the South African gold mines. This needs to be recalculated over the expected SW (Equation 9). These grades (in g/t) would be in the first column. The area (in m^2) and the SW (in cm) would populate the second and third columns. The resource category (Measured or Indicated) would be in the fourth column. For the Excel model to be able to sum the Measured and Indicated tonnage totals (for checking against the published figures), the typical M and I coding would be replaced by 1 (Measured) and 2 (Indicated). The cells where data is input are shown in grey, with the formulae in the white cells.

The columns of the block listing are shown in Figure A-2.

	A	B	C	D	E	F
1	**Table 1. Block Listing**					
2	**Est SW g/t**	**M2**	**SW**	**Catagory**	**SW Tonnes**	**Face Grams**
3	9.31	900	136	1	3,329	31,010
4	7.95	900	136	1	3,329	26,473
5	7.58	900	136	1	3,329	25,252
6	7.19	900	136	1	3,329	23,931
7	9.58	900	136	1	3,329	31,885
8	8.75	900	136	1	3,329	29,124
9	10.88	900	136	1	3,329	36,233
10	10.02	900	136	1	3,329	33,347
11	9.25	900	136	1	3,329	30,790
12	10.50	900	136	1	3,329	34,957
13	6.87	900	136	1	3,329	22,881
14	8.44	900	136	1	3,329	28,104
15	4.96	900	136	1	3,329	16,519
16	4.72	900	136	1	3,329	15,729

Figure A-2. Block listing input columns.

For this study, block lists have been simulated from the information available in the public domain (the Annual Mineral Resource and Reserve Statements). This simulation process was conducted by determining the grade-tonnage profile from the various companies' grade-tonnage curves presented in these annual reports. Distributions for the profiles were obtained using the Palisade @Risk program.

The number of Measured blocks was determined from the Measured tonnes, SW and stated block size (for example, 136 cm and 30 x 30 m for Kusasalethu Mine). The same exercise was repeated for the Indicated blocks using 60 x 60 m blocks. The grade distribution was then used to generate a grade for each block that the overall grades matched the published Measured and Indicated grades.

This reverse approach would not be required if this study was conducted on a mine where the block list was provided, as it is the source of the grade-tonnage curve, not its result. Because this study primarily compares the effects of the different approaches in considering the costs of the mineral resource royalty, this approach to generating the block lists is considered acceptable because the errors would be the same for all the approaches being compared. It so would not affect the overall findings of the research.

Table A-I shows the fifth and sixth columns, and the following Excel functions are used in Columns E and F (Equations 7 and 10).

Table A-I. Table 1 Block Listing.

Value	**Excel Function**	**Comment**
SW Tonnes	=B3*C$3/100*J$5 Repeats for all rows	The tonnes from the SW (converted from cm to m), m^2, and SG are calculated.
Face Grams	=A3*E3 Repeats for all rows	Calculates the gold content from the grade (g/t) and tonnes.

Table 2. Input table (Cashflow Sheet)

The input table is where all the parameters required for the BirchOptimiser to run are input into the model. The input values used for this thesis for Kusasalethu Mine are shown in Figure A-3.

	A	B	C
3	**Table 2. Input Table**		
4	**Kusasalethu**		
5	Measured Resource Tonnes	tonnes	3,400,000
6	Indicated Resource Tonnes	tonnes	12,600,000
7	Specific Density	t/m2	2.72
8	Planned Annual Milled Tonnes	tonnes	708,000
9	% Stope to Milled Tonnes	%	82.4%
10	Planned SW	cm	136
11	Planned MW	cm	165
12	Gold Price	US$/oz t	$1,799
13	MRF	%	81.7%
14	Initial CapEx	US$ millions	$0.0
15	Discount Rate	%	12.0%
16	Labour Cost Proportion	%	55.1%
17	Salary Proportion	%	50.0%
18	Estimated Employee Average Tax Rate	%	18.0%
19	Taxes Borne	%	7.5%
20	All-in-Sustaining Cost (Including Royalty)	US$/tonne	$272.39
21	Estimated Royalty Costs	US$/tonne	$9.66
22	All-in-Sustaining Cost (Excl Royalty)	US$/tonne	$262.73

Figure A-3. BirchOptimiser input table.

All the information required for the analysis conducted for this thesis is available in the public domain, predominantly from the Annual Mineral Resource and Reserve Statements. Many of the required figures would be obtained on the mine from the Ore Flow document (described in Chapter 5.2.2 and Figure 5-1). Table A-II shows the input sources and Excel functions (For Column C) used for this thesis for Kusasalethu Mine in Table 2.

Table A-II. Kusasalethu Mine inputs to Table 2.

Value	Excel Function	Comment
Kusasalethu		Mine Name.
Measured Resource Tonnes		From Annual Resource and Reserve Statement - check against the Block Listing.
Indicated Resource Tonnes		From Annual Resource and Reserve Statement - check against Block Listing.
Specific Density		From Ore Flow.
Planned Annual Milled Tonnes		From Annual Resource and Reserve Statement.
% Stope to Milled Tonnes	=C10/C11	From the Ore Flow or Calculated.
Planned SW		From Annual Resource and Reserve Statement or Ore Flow.
Planned MW		The planned SW and MW can be used to determine the % Stope to Milled tonnes if the Ore Flow is not available.
Gold Price		Planned gold price.
MRF		From the Ore Flow or Annual Resource and Reserve Statement.
Initial CapEx		Only input if mine has substantial capital outstanding. This is used for the unredeemed CapEx tax shield. All the mines included in the study are mature mines and so were not considered to have unredeemed CapEx.
Discount Rate		From the Annual Financial Report.
Labour Cost Proportion		From the Annual Financial Report.
Salary Proportion		Proportion of labour cost that is salaries
Estimated Employee Average Tax Rate		Based on SARS Tax Scales
Taxes Borne		Additional sources of revenue to the state (Levies, taxes paid by suppliers etc.)
All-in-Sustaining Cost (Including Royalty)		From Annual Resource and Reserve Statement.
Estimated Royalty Cost		This value is estimated using the break-even grade, including the royalty cost.
All-in-Sustaining Cost (Excl Royalty)	=C20-C21	The mining cost excluding mineral resource royalty costs.

Table 3. Cut-off grade input table (Cashflow Sheet)

This is the table where the cut-off grade is input into the model. This also contains the Excel Solver's variable cell to determine the optimal value for the profit or NPV. This table also brings in the results from the optimisation of the Optimiser Output (Table 4) on the Blocklist sheet into the Cashflow Sheet so that they can be linked to the cash flow model. This table is shown in Figure A-4.

	A	B	C
25	**Table 3. Cut-off Grade Input**		
26	Cut-off Grade	g/t	6.60
27	Gold Price	US$/g	$57.85
28	AMG	g/t	9.24
29	Total Stope Tonnes above Cut-Off	tonnes	10,433,964
30	Planned Annual Stope Tonnes	tonnes	583,564
31	Planned Additional Milled Tonnes	tonnes	124,436

Figure A-4. Cut-off grade input table.

Table A-III shows the inputs and Excel functions (for Column C) in Table 3.

Table A-III. Table 3 inputs and Excel functions.

Value	**Excel Function**	**Comment**
Cut-off Grade		**Use Solver to determine this value (Variable).**
Gold Price	=C12/31.1	Calculated from the US$/oz gold price for use in the break-even grade calculations
AMG	='Blocklist Sheet'!L9	The average grade of the blocks above the cut-off grade
Total Stope Tonnes above Cut-Off	='Blocklist Sheet'!L6	Output from the block listing depending on the cut-off grade
Planned Annual Stope Tonnes	=C8*C9	Determined from the milled to stope tonnage ratio.
Planned Additional Milled Tonnes	=C8-C30	Dilution tonnes (determined from the milled to stope tonnage ratio

Table 4. Optimiser output (Blocklist Sheet)

This table links the cut-off grade from Table 3 back to the Block Listing (shown in Figure A-5). The Excel functions in this table determine the stope tonnes above the selected cut-off grade and the average grade for the tonnes available. These figures are then used in the cash flow (Table 5) for the financial analysis.

	J	K	L
1	**Table 4. Optimiser Output**		
2	Total Measured (1) Tonnes	tonnes	3,399,195
3	Total Indicated (2) Tonnes	tonnes	12,597,996
4	Cut-off g/t	g/t	6.60
5	SG	t/m2	2.72
6	Total Stope Tonnes	tonnes	10,420,646
7	Average SW of blocks above cut-off	cm	136
8	Face Grams	grams	96,322,157
9	AMG	g/t	9.24

Figure A-5. Optimiser Output table.

The BirchOptimiser uses the Excel SUMIF function to interrogate the Block List and identify all the blocks with a grade above the cut-off grade. This table also has a check function so that the Measured and Indicated block tonnage in the Block List can be compared to the Measured and Indicated tonnages from the Mineral Resource and Reserve Statement. The study into the impact of the Mineral Resource Royalties used simulated block lists, so the tonnage check was included to ensure the data in the block list was valid. Table A-IV shows the outputs and Excel functions (for Column K) found in Table 4.

Table A-IV. Outputs and Excel functions in Table 4.

Value	Excel Function	Comment
Total Measured (1) Tonnes	=SUMIF(E:E,"="&1,F:F)	Check against mineral resource tonnes
Total Indicated (2) Tonnes	=SUMIF(E:E,"="&2,F:F)	Check against mineral resource tonnes
Cut-off g/t	='Cashflow Sheet'!C26	From the BirchOptimiser
SG	='Cashflow Sheet'!C7	Density
Total Stope Tonnes	=SUMIF(A:A,">"&L4,F:F)	Resultant available stope tonnes above cut-off
Average SW of blocks above cut-off	=AVERAGEIF(A:A,">"&L4,D:D)	Average SW of the blocks above the cut-off grade
Face Grams	=SUMIF(A:A,">"&L4,G:G)	Total gold content of the blocks above the cut-off grade
AMG	=L8/L6	Resultant average mining Grade (AMG)

Table 5. Cash Flow (Cashflow Sheet)

The financial model within the BirchOptimiser has been adopted from the cash flow model presented at the University of the Witwatersrand School of Mining for the various Mine Financial Valuation courses (BSc (Eng) and MSc) (School of Mining Engineering, 2021b). This is shown for the first few years of the Kusasalethu example in Figure A-6. The cash flow can be expanded and adapted to fit into any company-reporting format as required. A very simple cash flow could be used for this thesis, which only uses the AISC minus the royalties as the cost input.

	A	B	C	D	E	F	G
34	**Table 5. Cash Flow**						
35	**Kusasalethu**						
36		Calendar Year	2021	2022	2023	2024	2
37		Project Year	0	1	2	3	
38		Units		1	1	1	
39	**Production**						
40	Stope Tonnes Remaining	tonnes		10,420,646	9,837,083	9,253,519	8,669,
41	Annual Stope Tonnes	tonnes		583,564	583,564	583,564	583,
42	Annual Milled Tonnes	tonnes		708,000	708,000	708,000	708,
43	In-Situ AMG	g/t		9.24	9.24	9.24	9
44	MRF	%		81.7%	81.7%	81.7%	81
45	Gold Produced	g		4,406,988	4,406,988	4,406,988	4,406,
46	Gold Produced	oz		141,704	141,704	141,704	141,
47	**Revenue**						
48	US Gold Price	$/oz		$1,799	$1,799	$1,799	$1,
49							
50	**Gross Sales Revenue**	US$ millions		**$254.93**	**$254.93**	**$254.93**	**$254**
51	**Costs**						
52	All-in-Sustaining Cost (Excluding Royalties)	US$/t		($262.73)	($262.73)	($262.73)	($262
53	**Total Costs**	US$ millions		**($186.01)**	**($186.01)**	**($186.01)**	**($186**
54							
55	**Earnings Before Interest and Tax (EBIT)**	US$ millions		**$68.91**	**$68.91**	**$68.91**	**$68**
56	**Capital Expenditure and Tax Shield**						
57	Capital Expenditure (Nominal)	US$ millions	**$0.0**				
58	Gold Mine Capital Allowance (12%)	US$ millions		$0.00	$0.00	$0.00	$0
59	Unredeemed Capex	US$ millions	$0.0	$0.00	$0.00	$0.00	$0
60							
61	**Net Sales Revenue after Capex**	US$ millions		**$68.91**	**$68.91**	**$68.91**	**$68**
62	**Royalties**						
63	**EBIT for Royalty Calculation**	%		**$68.91**	**$68.91**	**$68.91**	**$68**
64	X=(EBIT Royalty /Gross Sales)			27.03	27.03	27.03	2
65	Refined Royalty Rate (Y=0.5+(X/12.5)	%		2.66%	2.66%	2.66%	2.
66	**Royalty Paid**	US$ millions		**($6.79)**	**($6.79)**	**($6.79)**	**($6**
67	**Income Tax**						
68	Taxable Income	US$ millions		$62.12	$62.12	$62.12	$62
69	X=(Taxable Income/Gross Sales)	%		24.37	24.37	24.37	24
70	Gold Tax Rate (34-170/X)	%		27.02%	27.02%	27.02%	27.
71	**Income Tax Payable**	US$ millions		**($16.79)**	**($16.79)**	**($16.79)**	**($16**
72	**Cash Flow**						
73	**Actual Cash flow after tax**	US$ millions	**$0.0**	**$45.34**	**$45.34**	**$45.34**	**$45**
74	**Discounted Cash flow**	US$ millions	**12.0%**	**$40.48**	**$36.14**	**$32.27**	**$28**
75	**NPV**	US$ millions	**$327.83**				

Figure A-6. Cash flow table.

It can be observed that the BirchOptimiser cash flow table is split into components. These are:

- Production;
- Revenue;
- Costs;

- Capital expenditure and tax shield;
- Royalties;
- Income tax; and
- Cash flow.

Production

The annual planned milled tonnage is obtained from the Annual Mineral Resource and Reserve Statement for the various mines included in the study. The milled-to-stope tonnage ratio determines the proportion of the milled tonnes comprised of stope tonnes. This ratio considers the additional dilution tonnes (from the stopes and other sources). The stope tonnes are considered only the tonnes derived from the stopes at the SW. In-stope sources, for example, gulleys and off-reef mining, add to the milled tonnes but do not contribute significant amounts of extra gold. This is also taken into consideration for the break-even grade calculation.

The number of years the mine operates is determined by the available stope tonnes above the cut-off grade resulting from the selected cut-off grade. The AMG is determined from the block listing grams above cut-off grade divided by the stope tonnes above cut-off grade. The MRF (Equation 15) determines the amount of gold contributing to the revenue and considers the estimation uncertainties, production efficiencies and plant recovery losses. The gold produced is the stope tonnage multiplied by the AMG and MRF (Equation 16). Table A-V shows the values and Excel functions (for Columns D and E).

Table A-V. Table 5 production inputs and Excel functions.

Value	Excel Function	Comment
Stope Tonnes Remaining	=C29 For Column D =IF(D40>0,D40-D41,D40) From Column E and repeats for all columns	Depletes the tonnes remaining with the production from the previous year.
Annual Stope Tonnes	=C8*C9 For Column D =IF(E40>D41,D41,E40) From Column E and repeats for all columns	If there are tonnes available, the annual production tonnes are used. The remaining tonnes will be used if fewer tonnes are available than a full year's production.
Annual Milled Tonnes	=C8 For Column D =IF(E41>0,E41/$C9,0) From Column E and repeats for all columns	Uses the stope to milled tonne ratio to determine the annual milled tonnes (does not contribute to the gold produced but is used for determining the total costs.
In-Situ AMG	=$C28 Repeats for all columns	The AMG is determined from the block listing.
MRF	=$C13 Repeats for all columns	
Gold Produced	=D41*D43*D44 Repeats for all columns	Stope tonnage multiplied by AMG and MRF to determine the gold produced in grams
Gold Produced	=D45/31.1 Repeats for all columns	Converts the grams produced to ounces produced.

Revenue

The GSR (in US$) is determined from the gold produced (in oz) multiplied by the price (in US$/oz) (Equation 17). The values and Excel functions (for Column D) are shown in Table A-VI.

Table A-VI. Table 5 revenue inputs and Excel functions.

Value	Excel Function	Comment
US$ Gold Price	=$C12 Repeats for all columns	Reported in US$/oz
Gross Sales Revenue	=D48*D46/1000000 Repeats for all columns	Revenue is reported in US$ millions.

Costs

Companies report their AISC in the Annual Mineral Resource and Reserve Report. This total cost (US$/tonne) includes the Mineral Resource Royalty cost. For the BirchOptimiser, the royalty cost must be subtracted from the AISC because the model adds the royalty costs. Table A-VII shows the values and Excel functions (for Column D).

Table A-VII. Table 5 costs inputs and Excel functions.

Value	Excel Function	Comment
All-in-Sustaining Cost (Excluding Royalties)	=$C22*-1 Repeats for all columns	Mining costs are reported as negative numbers
Total Costs	=D52*D42/1000000 Repeats for all columns	Reported in US$ millions

Earnings before interest and tax

The EBIT is obtained by subtracting the total costs from the GSR (Equation 18). The values and Excel functions (for Column D) are shown in Table A-VIII.

Table A-VIII. Table 5 EBIT inputs and Excel functions

Value	Excel Function	Comment
Earnings before interest and tax	=D50+D53 Repeats for all columns	Reported in US$ millions

Capital costs and tax shield

The South African Revenue Service allows the total capital costs to be redeemed in the year they are incurred and any unredeemed capital to roll over to the following year. Furthermore, for gold mines, the unredeemed capital at the year-end is allowed a 12% capital allowance (School of Mining Engineering, 2021b). The mines included in this thesis research study are mature mines, and the initial capital is considered fully redeemed.

Sustaining (also called stay-in-business) capital is included in the AISC and does not appear as an additional capital cost. However, the BirchOptimiser has the functionality to include initial capital costs in the financial model. Table A-IX shows the values and Excel functions for Columns C, D and E for the initial capital, along with the capital allowance and tax shield.

Table A-IX. Table 5 capital costs and tax shield inputs and Excel functions.

Value	Excel Function	Comment
Capital Expenditure (Nominal)	=C14*-1 In Column C	For simplicity, the initial capital is considered a lump sum and included in Year 0 of the model. This capital can be spread out over subsequent years if the mine is in the build-up stage and the production only commences in later years. Capital costs reported as negative numbers
Gold Mine Capital Allowance (12%)	=C59*0.12 In Column D =IF(D59<0,D59*0.12,0) From Column E and repeats for all columns	
Unredeemed Capex	=C57 In Column C =IF(C59+D55+D57+D58<0,C59+D55+D57+D58,0) From Column D and repeats for all columns	The income is shielded from income tax, and the profitability ratio of the royalty calculation is zero until all the outstanding capital is redeemed.

Royalties

The mines included in this thesis study deliver their gold to the Rand Refinery in Germiston, Gauteng. Using the refined royalty rate, they can pay the mineral resource royalty (Equation 2). Table A-X shows the values and Excel functions (for Column D).

Table A-X. Table 5 royalty inputs and Excel functions.

Value	Excel Function	Comment
EBIT for Royalty Calculation	=IF(D59<0,0,C59+D55+D58) Repeats for all columns	This would be zero when still shielded by unredeemed capital
X=(EBIT Royalty /Gross Sales)	=IF(D55>0,D63/D50*100,0) Repeats for all columns	
Refined Royalty Rate (Y=0.5+(X/12.5)	=(IF(0.5+(D64/12.5)<5,0.5+(D64/12.5),0.5))/100 Repeats for all columns	Even if the EBIT is zero or negative, the minimum rate would be 0.5% of gross revenue
Royalty Paid	=IF(D50<0,0,D65*D50)*-1 Repeats for all columns	Royalty costs are reported as negative numbers

Income tax

South African gold mines pay income tax determined using the gold tax formula (Equation 4). All other commodities pay income tax using the corporate tax rate (currently 27%) (School of Mining Engineering, 2021b). The values and Excel functions (for Column D) are shown in Table A-XI.

Table A-XI. Table 5 income tax inputs and Excel functions.

Value	Excel Function	Comment
Taxable Income	=IF(D63>0,D63+D66,0) Repeats for all columns	
X=(Taxable Income/Gross Sales)	=IF(D68>0,D68/D50*100,0) Repeats for all columns	
Gold Tax Rate (34-170/X)	=IF(D69>0,34-(170/D69),0)/100 Repeats for all columns	
Income Tax Payable	=IF(D70>0,D70*D68*-1,0) Repeats for all columns	Income tax costs reported as negative numbers

Cash flow

Table A-XII shows the values and Excel functions (for Columns C and D) for the cash flow (Equation 19) and DCF (Equation 20).

Table A-XII. Table 5 cash flow inputs and Excel functions.

Value	Excel Function	Comment
Actual Cash flow after tax	=C57 In Column C =D55+D66+D71 From Column D and repeats for all columns	
Discounted Cash flow	=C15 In Column C =(1/($C74+1)^D37)*D73 From Column D and repeats for all columns	
NPV	=NPV(C74,D73:AM73)+C73 In Column C	
IRR	=IRR(C73:AM73) In Column C	An internal rate of return (IRR) can only be determined if an initial capital amount is included. For this thesis research, none of the mines has initial capital included in the analysis so no IRRs could be determined.

Totals

The cash flow model is expanded to include as many years as required by the mine being evaluated. It is crucial that the financial model accommodates even the lowest cut-off grade (in other words, the entire Mineral Resource). If this is not the case, the possibility of incorrect cut-off grades being determined by the BirchOptimiser because not all the possible revenue generated for the corresponding cut-off grade is considered.

Totals are determined for various values, including:

- Stope tonnes;

- Milled tonnes;
- Gold produced;
- Gross sales revenue;
- Costs;
- EBIT;
- Capital expenditure;
- Royalties paid;
- Income tax paid;
- Undiscounted cash flow; and
- DCF.

The totals column (Column AN) can be viewed in Figure A-7.

	A	B	AN
34	**Table 5. Cash Flow**		
35	**Kusasalethu**		
36		Calendar Year	**Totals**
37		Project Year	
38		Units	**18**
39	**Production**		
40	Stope Tonnes Remaining	tonnes	
41	Annual Stope Tonnes	tonnes	**10,420,646**
42	Annual Milled Tonnes	tonnes	**12,642,696**
43	In-Situ AMG	g/t	
44	MRF	%	
45	Gold Produced	g	**78,695,203**
46	Gold Produced	oz	**2,530,392**
47	**Revenue**		
48	US Gold Price	$/oz	
49			
50	**Gross Sales Revenue**	US$ millions	**$4,552.18**
51	**Costs**		
52	All-in-Sustaining Cost (Excluding Royalties)	US$/t	
53	**Total Costs**	US$ millions	**($3,321.62)**
54			
55	**Earnings Before Interest and Tax (EBIT)**	US$ millions	**$1,230.56**
56	**Capital Expenditure and Tax Shield**		
57	Capital Expenditure (Nominal)	US$ millions	**$0.00**
58	Gold Mine Capital Allowance (12%)	US$ millions	
59	Unredeemed Capex	US$ millions	
60			
61	**Net Sales Revenue after Capex**	US$ millions	**$1,230.56**
62	**Royalties**		
63	**EBIT for Royalty Calculation**	%	
64	X=(EBIT Royalty /Gross Sales)		
65	Refined Royalty Rate (Y=0.5+(X/12.5)	%	
66	**Royalty Paid**	US$ millions	**($121.21)**
67	**Income Tax**		
68	Taxable Income	US$ millions	**$1,109.35**
69	X=(Taxable Income/Gross Sales)	%	
70	Gold Tax Rate (34-170/X)	%	
71	**Income Tax Payable**	US$ millions	**($299.79)**
72	**Cash Flow**		
73	**Actual Cash flow after tax**	US$ millions	**$809.56**
74	**Discounted Cash flow**	US$ millions	**$327.83**
75	**NPV**	US$ millions	

Figure A-7. Cash flow totals.

For each value, the total is determined using an =SUM(Dxx:AMxx), with xx being the row in which the value is.

Table 6. Output table (Cashflow Sheet)

The output table presents the analysis findings. This table is shown in Figure A-8.

	A	B	C
80	**Table 6. Output Table**		
81	**Kusasalethu**		
82	Break-even Grade Including Royalty Cost	g/t	6.99
83	Break-even Grade Excluding Royalty Cost	g/t	6.74
84	Optimised Cut-off Grade	g/t	6.60
85	Total Stope Tonnes	tonnes	10.42
86	Total Milled Tonnes	tonnes	12.64
87	LoM	years	18
88	AMG	g/t	9.24
89	Profit	US$	$809.56
90	NPV	US$	$327.83
91	Average Royalty Rate	%	2.66%
92	Average Gold Tax Rate	%	27.02%
93	Total Revenue	US$	$4,552.18
94	Total Mining Costs	US$	($3,321.62)
95	Total Royalties	US$	($121.21)
96	Total Income Tax (gold tax)	US$	($299.79)
97	Total Tax Contribution	US$	($927.13)

Figure A-8. Output table.

Table A-XIII shows the outputs and Excel functions (for Column C).

Table A-XIII. Table 6 outputs and Excel functions.

Value	Excel Function	Comment
Kusasalethu		Mine Name
Break-even Grade Including Royalty Cost	=C20/(C12/31.1)/(C13*C9)	Calculated to compare to optimised cut-off grade
Break-even Grade Excluding Royalty Cost	=C22/(C12/31.1*C9*C13)	Calculated to compare to optimised cut-off grade
Optimised Cut-off Grade	=C26	Output from optimiser
Total Stope Tonnes	=AN41/1000000	From Table 5
Total Milled Tonnes	=AN42/1000000	From Table 5
LoM	=AN38	From Table 5
AMG	=C28	From Table 3
Profit	=AN73	From Table 5 **Use Solver to optimise this for maximum profit (Objective)**
NPV	=C75	From Table 5 **Use Solver to optimise this for maximum NPV (Objective)**
Average Royalty Rate	=AN66*-1/AN50	From Table 5 This shows the difference between estimated royalty and optimised royalty rates
Average Gold Tax Rate	=AN71*-1/AN68	From Table 5
Total Revenue	=AN50	From Table 5
Total Mining Costs	=AN53	From Table 5
Total Royalties	=AN66	From Table 5
Total Income Tax (gold tax)	=AN71	From Table A-5
Total Tax Contribution	=AN66+AN71+(AN53*C17*C16*C18)+(AN50*C19*-1)	

A1.3 Excel Solver Optimiser

The BirchOptimiser utilises the Excel Solver function to determine the optimal cut-off grade considering the desired output (described in Chapter 5.3). The Solver function needs to be activated before it is available. This is done by going to Excel Options, selecting the Add-ins and then selecting Manage: Excel Add-ins, as shown in Figure A-9.

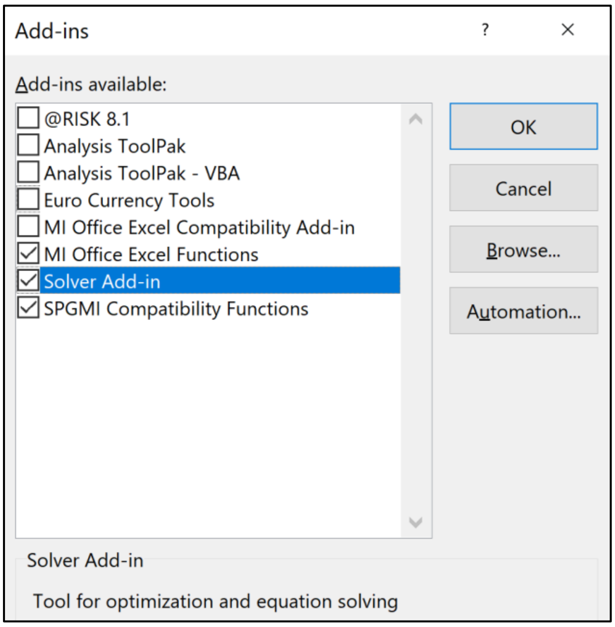

Figure A-9. Activating the Excel Solver function.

Selecting the Solver function is done in the Excel ribbon Data tab, which is found to the far right of this ribbon. It indicates that it has not been activated if it is not displayed there. When the Solver function is selected, the Solver Parameter input panel is activated, as shown in Figure A-10. This panel allows for selecting the Objective cell (either profit or NPV) and the Variable cell (cut-off grade).

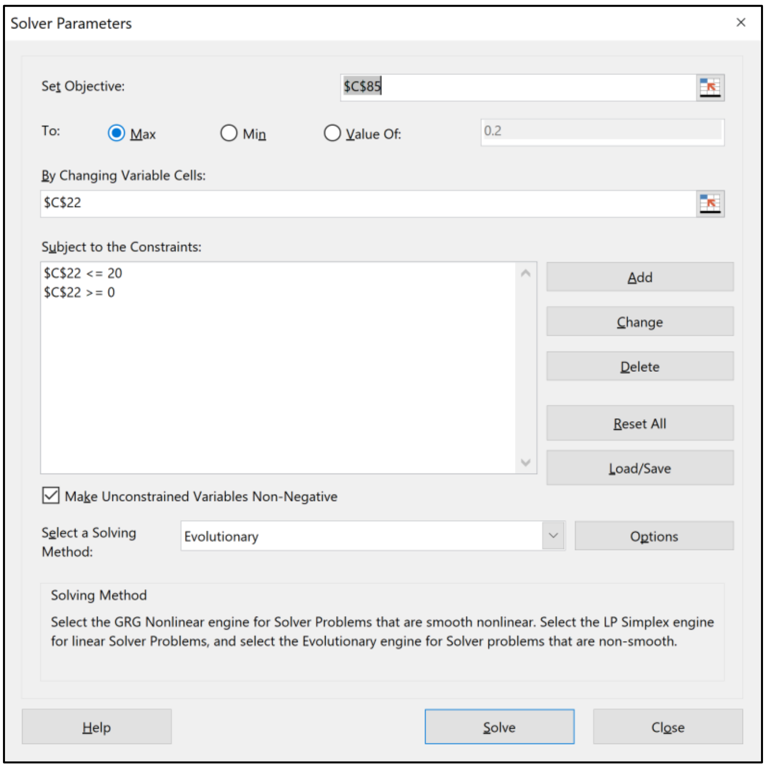

Figure A-10. Excel Solver Parameter input panel.

The objective can be set to maximise either the profit (Cell C85 in Table 6) or NPV (Cell C86 in Table 6). The cut-off grade, the variable that the Solver will vary to maximise the objective, is in Cell C22 in Table 3. The one limitation Solver has is that both the objective and variable must be on the same sheet. For example, the cut-off grade variable cell cannot be on the Blocklist Sheet, and yet there can be a link to the Cashflow Sheet C22 cell on the Blocklist Sheet to enable the =SUMIF functions to operate).

Solver has three methods that it could use to find the optimal solution. These are GRG nonlinear, Simplex LP and Evolutionary. It has been found that only the Evolutionary method works for the BirchOptimiser. For the Evolutionary method to be used, constraints to the range of values for the variable it will be adjusting need to be specified. In the case of the BirchOptimiser, the minimum cut-off grade is specified as 0 g/t (it must be a positive value), and 20 g/t is selected as the maximum cut-off grade. This range is appropriate for all the mines included in the study for both the profit and NPV optimisation approaches.

The Evolutionary method is prolonged. The process can be shortened by adjusting the *maximum time without improvement* in the Options Evolutionary panel (Figure A-11. Five seconds are sufficient for the BirchOptimiser, which only requires cut-off grade accuracy to two decimal places.

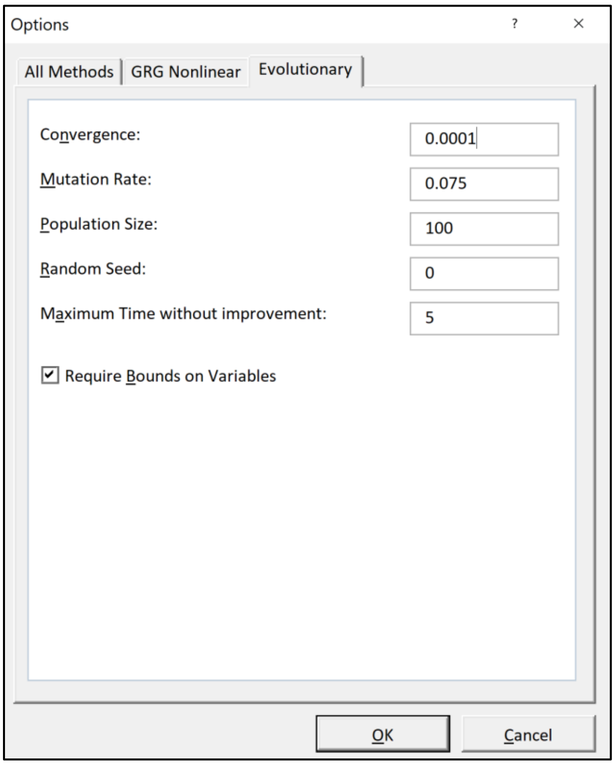

Figure A-11. Solver Options panel for the Evolutionary method.

Once the Solver is set up, the process can be run. When a solution has been found, the optimal value for the cut-off grade will be found to have been inserted in Cell C22 in Table 3.

A1.4 Constructing the Grade-Tonnage Graph

The output of the BirchOptimiser can be displayed visually using the commonly used grade-tonnage curve (Figure A-12). A separate Excel sheet is used to create these graphs (GT Curve Sheet). The Estimated SW g/t, SW Tonnes, and Face Grams columns from the Blocklist Sheet are used to create the graph.

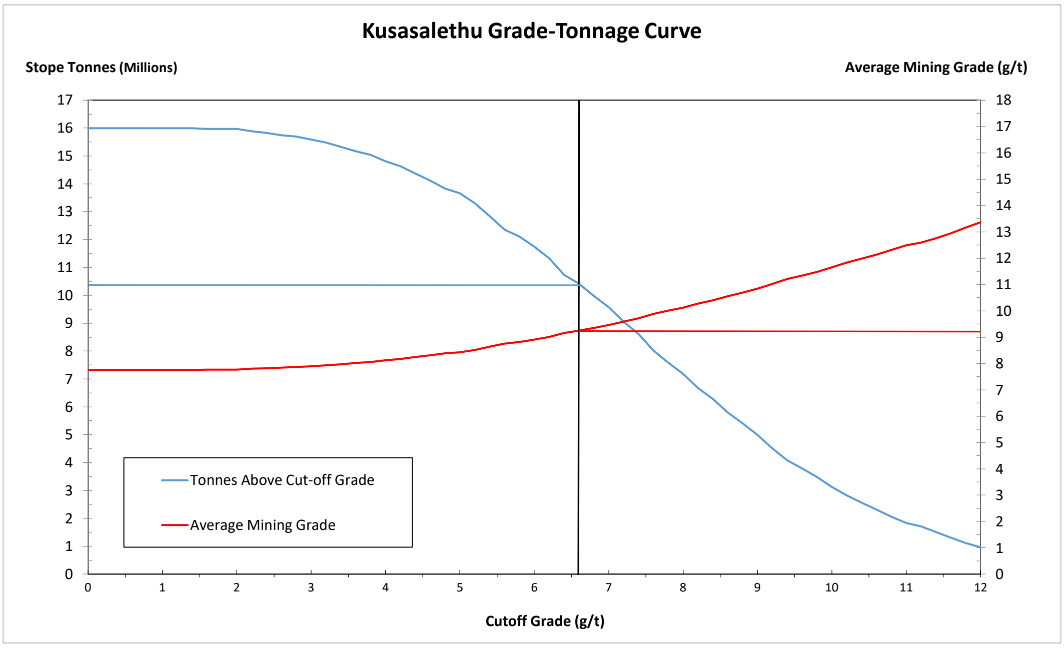

Figure A-12. The grade-tonnage curve for Kusasalethu. The cut-off grade is 6.60 g/t, with stope tonnage above the cut-off grade of 10.4 million tonnes at an average mining grade of 9.24 g/t.

The generation of the data point lines for the graph uses the same =SUMIF function as used in the BirchOptimiser to determine the stope tonnes and AMG for the various cut-off grades. The cut-off grade range for the graph, as demonstrated in the Kusasalethu example, is from 0 g/t to 12 g/t in 0.2 g/t intervals (Figure A-13).

	A	B	C	D	E	F
1	Cut-off Grade	0	0.2	0.4	0.6	
2	Tonnes Above Cut-off Grade	15,997,190	15,997,190	15,997,190	15,997,190	15,997,
3		16.00	16.00	16.00	16.00	16
4	Face Grams	124,091,941	124,091,941	124,091,941	124,091,941	124,091,
5	Average Mining Grade	7.76	7.76	7.76	7.76	7.

Figure A-13. Data points for creating the grade-tonnage curve.

Table A-XIV shows the outputs and Excel functions (for Column B) required for creating the grade-tonnage graph.

Table A-XIV. Grade-tonnage curve graph outputs and Excel functions.

Value	**Excel Function**	**Comment**
Cut-off Grade	0	In 0.2 g/t intervals
Tonnes Above Cut-off Grade	=SUMIF('Blocklist Sheet'!$A:$A,">"&B1,'Blocklist Sheet'!$F:$F) From Column B and repeats for all columns	
	=B2/1000000 From Column B and repeats for all columns	Displays the tonnage in millions
Face Grams	=SUMIF('Blocklist Sheet'!$A:$A,">"&B1,'Blocklist Sheet'!$G:$G) From Column B and repeats for all columns	
Average Mining Grade	=B4/B2 From Column B and repeats for all columns	

The graph's horizontal axis is Row 1 for the tonnage above the cut-off grade and the AMG. For the tonnage above cut-off grade, Row 3 is selected, whilst for the AMG, Row 5 is selected.

The vertical (black) line is manually moved to the position of the cut-off grade. The blue horizontal line is manually moved to where the cut-off line intersects the blue tonnage line. The intersection with the left vertical axis should be the value of the tonnes above the cut-off grade. The red horizontal line is manually moved to where the cut-off grade intersects the red grade line. The intersection with the right vertical axis should be the value of the AMG (see Figure A-12 for the positions of the vertical and horizontal lines).

A1.5 Cut-off Grade Considering Grade Estimation Uncertainties

Only two changes are required to the BirchOptimiser to optimise the cut-off grade considering grade estimation uncertainties. These changes are to Table 1 on the Blocklisting Sheet (Figure A-14). The first change is the inclusion of an additional column to the right of the SW g/t column (renamed to Estimated SW g/t). This new column (Act SW g/t) is populated with grades generated using @Risk. For Kusasalethu Mine, a Laplace distribution with a standard deviation of 3.23 g/t has been used to model the 'actual' grade for each block (Chapters 8.22 and 8.23). The distributions' tails are clipped to prevent negative block grades and keep the overall grades the same.

	A	B	C	D	E	F	G
1	**Table 1. Block Listing**						
2	**Est SW g/t**	**Act SW g/t**	**M2**	**SW**	**Catagory**	**SW Tonnes**	**Face Grams**
3	9.31	5.88	900	136	1	3,329	19,585
4	7.95	9.95	900	136	1	3,329	33,128
5	7.58	7.47	900	136	1	3,329	24,863
6	7.19	8.44	900	136	1	3,329	28,098
7	9.58	8.20	900	136	1	3,329	27,289
8	8.75	5.24	900	136	1	3,329	17,438
9	10.88	11.71	900	136	1	3,329	38,997
10	10.02	12.65	900	136	1	3,329	42,101
11	9.25	11.07	900	136	1	3,329	36,854
12	10.50	6.02	900	136	1	3,329	20,040
13	6.87	7.22	900	136	1	3,329	24,025
14	8.44	9.92	900	136	1	3,329	33,031
15	4.96	4.47	900	136	1	3,329	14,884
16	4.72	2.65	900	136	1	3,329	8,815
17	9.22	7.39	900	136	1	3,329	24,619

Figure A-14. Modified Table 1 to optimise cut-off grades considering grade estimation uncertainty (compare with Figure A-2 to see the difference in Face Grams).

The second change required is to the formulae in Column G. Instead of using the grade in Cell A to determine the Face Grams, the grade in Cell B is used. The grade selection to determine if a block should be mined is still determined by the estimated grade (Cell A). However, the ‘actual’ gold grams from the block are determined by the grade in Cell B. All other inputs, functions and outputs for the BirchOptimiser remain unchanged.

It is noted that for Kusasalethu Mine, the difference in cut-off grade when optimising for profit when taking grade uncertainty into account is minimal (7.07 to 7.00 g/t or about a 1% reduction in the cut-off grade). However, when optimising for $NPV_{12\%}$, the difference is more significant (8.79 to 8.56 or about a 2.5% reduction in the cut-off grade). The impact of the grade uncertainty and the suggested changes to the cut-off grade when optimising for profit are presented in Figure 8-8 for all the gold mines included in the study.

A1.6 Multiple-Criteria Cut-off Grade Optimisation

The BirchOptimiser is adapted to conduct multiple-criteria optimisation (Chapter 8.3) by adding three new tables to the model’s Cashflow Sheet. The first of these tables (Table 7) is shown in Figure A-15, and it identifies the various stakeholders and the criteria (objective) to maximise or set a specific outcome. For the Kusasalethu example presented in this overview of the BirchOptimiser, four stakeholders are identified. These are:

- Management;
- Investors;
- State; and
- Employees.

	A	B	C	D
100	**Table 7. Multiple-Criteria Cut-off Grade**			
101	**Stakeholder**	**Criteria to Optimise**	**Objective**	**Cut-off Grade**
102	Management	Maximise Profit	$809.56	6.60
103	Investors	Maximise NPV	$327.83	8.38
104	State	Maximise Total Tax Contribution	$927.13	5.10
105	Employees	Extend LoM	27.02%	2.40

Figure A-15. Table 7 shows the stakeholders and the criteria (Excel Solver objective) to maximise.

The criteria selected to maximise for each stakeholder group have been selected as follows:

- Management – Maximum profit;
- Investors – Maximum NPV (if an initial capital amount is specified and an IRR can be determined, this group could be split into those investors for which the higher NPV is preferable and those seeking the highest IRR);
- State – Maximum direct revenue to the state, which is the combination of income tax and mineral resource royalties;
- Employees – Extended life-of-mine (LoM), which has been determined as a minimum accepted profitability percentage (20% in this example).

Table A-XV shows the objectives and Excel functions (for Column C) in Table 7.

Table A-XV. Multiple-criteria cut-off grade objectives.

Value	Excel Function	Comment
Maximise Profit	=AN73	Use as Solver Objective to maximise profit - record the resultant cut-off grade
Maximise NPV	=AN74	Use as Solver Objective to maximise NPV - record the resultant cut-off grade
Maximise Total Tax Contribution	=((AN53*C17*C16*C18)+AN66+AN71+(AN50*C19*-1))*-1	Use as Solver Objective to maximise State revenue - record the resultant cut-off grade
Extend LoM	=D70	Use as Solver Objective to determine set profitability (example 20%) - record the resultant cut-off grade

The objective for the Solver function is selected to be Cell C102, Cell C103, Cell C104 and Cell C105, respectively, for each stakeholder criteria. The resultant cut-off grade is recorded in Cell D102, Cell D103, Cell D104 and Cell D105.

The weighting for each stakeholder criteria is input into Table 8, as shown in Figure A-16.

	A	B	C
108	**Table 8. Stakeholder Weighting**		
109	Management	**25%**	1.65
110	Investors	**25%**	2.10
111	State	**25%**	1.28
112	Employees	**25%**	0.60
113	**Multiple-criteria cut-off grade**		**5.62**

Figure A-16. Table 8, stakeholder-weighting input.

For the Kusasalethu example, the weighting for each stakeholder group is kept equal (25% of the total for each of the four groups). It can be noted in Figure 8-12 that the Investors and Employees criteria represent the two extreme cut-off grades for all the mines included in this study. Generally, the Management (profit) and State (maximum direct revenue to the State) criteria are aligned, which would be expected considering income tax is payable on profits and the South African mineral resource royalty has a profitability component in the determination of the rate.

Table A-XVI shows the Excel functions (for Column C) and the output formula used in Table 8.

Table A-XVI. Table 8 Excel functions and outputs.

Value	**Excel Function**	**Comment**
Management	=B109*D102	
Investors	=B110*D103	
State	=B111*D104	
Employees	=B112*D105	
Multiple-criteria cut-off grade	=SUM(C109:C112)	Replace the optimised cut-off grade (Cell C26 Table 3) with this value to populate the multiple-criteria cut-off grade output

The multiple-criteria cut-off grade is recorded and inserted into Cell C26. The results obtained using these multiple-criterion cut-off grades are presented in Table 9, as shown in Figure A-17.

	A	B	C	D
117	**Table 9. Multiple-Criteria Cut-off Grade Output Table**			
118	Weighted Cut-off Grade	g/t	**6.60**	
119	Total Stope Tonnes	tonnes	10.42	
120	Total Milled Tonnes	tonnes	12.64	
121	LoM	years	18	
122	AMG	g/t	9.24	
123	Profit	US$	$809.56	
124	NPV	US$	$327.83	
125	Average Royalty Rate	%	2.66%	
126	Average Gold Tax Rate	%	27.02%	
127	Total Revenue	US$	$4,552.18	
128	Total Mining Costs	US$	($3,321.62)	
129	Total Royalties	US$	($121.21)	
130	Total Income Tax (gold tax)	US$	($299.79)	
131	Total Tax Contribution	US$	($927.13)	

Figure A-17. Multiple-criteria cut-off grade output table.

Multiple-criteria cut-off grade graph

Figure A-18 is the output graph from the multiple-criteria cut-off grade optimisation. The four criteria selected are on the four corners of the graph. For the Kusasalethu example, the orange shaded area links the four cut-off grades (Profit, NPV, Tax and Royalty and LoM), whilst the red line displays the weighted average cut-off grade. This red line would move in and out depending on the weighting selected.

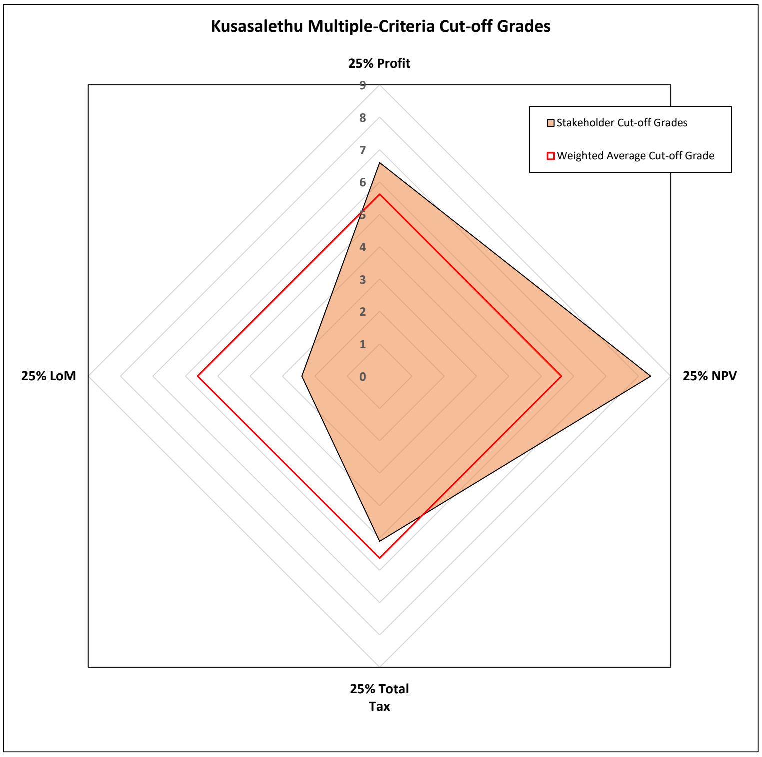

Figure A-18. Kusasalethu multiple-criteria cut-off grade output graph where each criterion is weighted 25%.

Effect of different weightings

The weighting of the different criteria would result from dialogue and negotiation between the different stakeholders. For Kusasalethu Mine, the Investors (maximise NPV) and Employees (extend the life of the mine) are noted to form the two extreme cut-off grade results (8.38 and 2.40 g/t, respectively). If the weighting selected is in favour of the Investors (for example, 70% with only 10% each for Management, the State and Employees), the weighted cut-off grade would be 7.28 g/t. If the weighting is in favour of the Employees' stakeholder group with 70% weighting (and 10% for each of the remaining three stakeholder groups), the weighted average cut-off grade would be 3.69 g/t. This is demonstrated in Figure A-19, where the two graphs show the resultant weighted cut-off grade for the two scenarios.

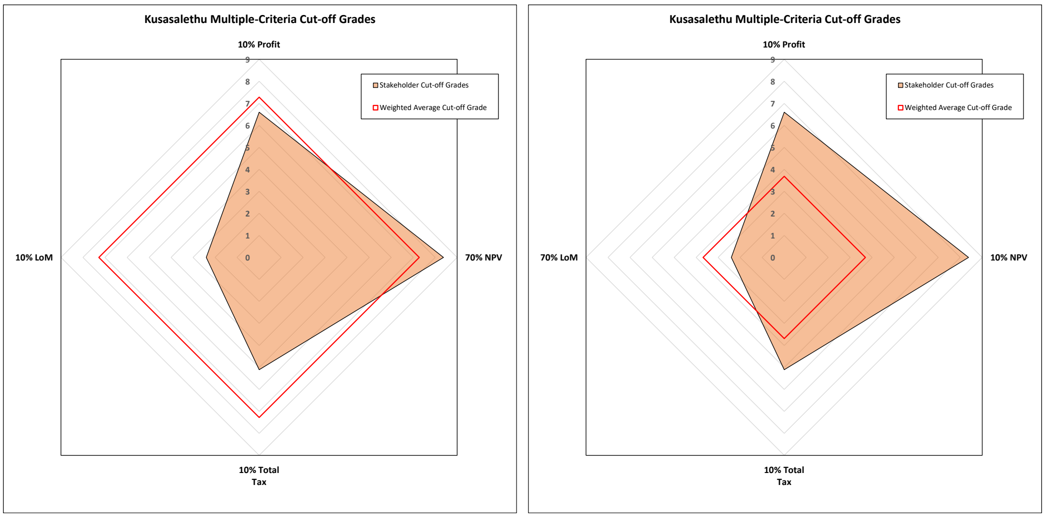

Figure A-19. The effect of changing the weighting of the output criterion from favouring the investor to favouring the employee stakeholder groups.

Table A-XVII shows the effect of changing the weightings.

Table A-XVII. Examples of different weighting for multiple-criteria optimisation for Kusasalethu Mine.

Value		**Evenly weighted**	**Weighted to favour Investors**	**Weighted to favour Employees**
Weighting	%	25% Each	70% NPV	70% LoM
Weighted Cut-off Grade	g/t	5.62	7.28	3.69
Total Stope Tonnes	tonnes	12.33	8.86	15.12
Total Milled Tonnes	tonnes	14.96	10.74	18.35
LoM	years	22	16	26
AMG	g/t	8.76	9.65	8.04
Profit	US$	$784.25	$793.25	$639.15
NPV	US$	$281.05	$357.51	$194.64
Average Royalty Rate	%	2.34%	2.91%	1.79%
Average Gold Tax Rate	%	25.78%	27.75%	22.10%
Total Revenue	US$	$5,107.11	$4,038.14	$5,743.09
Total Mining Costs	US$	($3,930.76)	($2,822.84)	($4,820.06)
Total Royalties	US$	($119.64)	($117.41)	($102.56)
Total Income Tax (gold tax)	US$	($272.46)	($304.63)	($181.33)
Total Tax Contribution	US$	($970.06)	($864.89)	($953.65)

The selected criterion can be adapted with further criteria added as different stakeholder groups are identified and preferred outcomes are determined. For example, if an initial CapEx amount and an IRR can be determined, the Investor stakeholder group could be split between those who favour the maximum NPV and those who would prefer the IRR to be maximised. The BirchOptimiser would allow many outputs (or even combinations of outputs) from the Table 5 Cash Flow to be used as an objective in the Solver function.

A1.7 Combining Grade Estimation Uncertainty with Multiple-Criteria Cut-off Grade Optimisation

The model created to explore grade estimation uncertainty can be combined with the multiple-criteria cut-off grade optimisation approach. The changes required to consider grade estimation uncertainty are described in A-5. For the Kusasalethu Mine example, the weighted average (25% weighting for each stakeholder) cut-off grade is compared to the same weighting criterion when grade estimation uncertainty is considered. The results are shown in Table A-XVIII.

Table A-XVIII. Multiple-criteria cut-off grade optimisation considering grade estimation uncertainty.

Stakeholder	**Criteria to Optimise**	**Cut-off Grade – No Grade Estimation Uncertainty**	**Cut-off Grade – With Grade Estimation Uncertainty**
Management	Maximise Profit	6.60	6.64
Investors	Maximise NPV	8.38	8.38
State	Maximise Tax Contribution	5.10	4.31
Employees	Extend LoM	2.40	2.40
Multiple-criteria cut-off grade (Even Weighting)		**5.62**	**5.43**

For Kusasalethu Mine, multiple-criteria cut-off grade optimising when grade estimation uncertainty is considered is very similar to the original values.

A1.8 Summary

The BirchOptimiser was developed to explore the impact of the Mineral Resource Royalty and determine the optimal approach to consider these costs when determining the cut-off grade. Whilst most of the gold mining countries and regions reviewed as part of this study determine the royalties using an *ad valorem* method (based on the value of the mineral sold), the South African royalties are determined using a hybrid approach. The rate is determined by considering the profitability of the minerals sold (also allowing the capital costs directly related to the winning and sale of the mineral) and then applying this rate to the total revenue derived from the sale of the mineral. Furthermore, the South African gold tax also considers profitability when determining the income tax rate (as opposed to the flat rate of 27% applied to all other commodities being mined).

Considering these unique sets of royalty and income tax specific to the South African gold mining industry, a cut-off grade optimisation model was developed to answer the above questions. The model combines the block listing and a cash flow, allowing the royalty rates to be easily altered as the various gold mines were considered. The optimal approach was identified and compared to the base case (a break-even cut-off grade with an estimated royalty rate). This has shown that the royalty costs should not be considered when determining the cut-off grade, and the interplay of the profitability of the royalty and gold tax rates allows a further reduction in the cut-off grade.

The flexibility of the BirchOptimiser was then used to explore other aspects of cut-off grade optimisation. These included whether the cut-off grade should be optimised to maximise the NPV or profit. Whilst it is shown that optimising to maximise the NPV severely influences the lives of the mines for a marginal increase in the NPV compared to maximising profit, this raised the question of how various stakeholders would wish the cut-off grade optimisation to take place. This has led to the development of a multiple-criteria cut-off grade approach where various stakeholder groups' interests are considered. Furthermore, grade estimation uncertainties have also been considered when determining the cut-off grade.

The BirchOptimiser described in this appendix will be developed further to consider the impact of the mineral resource block sizes on minable grades (if these differ from the SMU) and how these can be misleading to investors when they interpret the published grade-tonnage curves. The impact of proposed changes to income tax legislation (moving away from the gold tax formula and replacing this with a flat 27% rate) will also be explored.

The BirchOptimiser has been demonstrated with South African gold mines examples, and there is the scope for it to be adapted to any commodity for which cut-off grades are determined.

APPENDIX 2 MINE ROYALTY COST APPROACH ANALYSIS

A2.1 Doornkop Mine Analysis

Table A-XIX. Doornkop break-even and cut-off grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	5.33	
Break-even grade with no royalty costs	5.12	-3.94%
Profit-optimised cut-off grade with 0% royalty rate	5.02	-5.82%
Profit-optimised cut-off grade with 0.5% royalty rate	5.04	-5.44%
Profit-optimised cut-off grade with previous royalty costs	5.16	-3.19%
Profit-optimised cut-off grade with estimated royalty rate	5.17	-3.00%
Profit-optimised cut-off grade with 5.0% royalty rate	5.28	-0.94%
Profit-optimised cut-off grade with variable royalty rate	5.00	-6.10%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	5.97	12.06%

Table A-XX. Doornkop stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	5.35	
Stope tonnes above break-even grade with no royalty costs	5.78	7.97%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	5.99	12.02%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	5.96	11.35%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	5.73	7.03%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	5.71	6.70%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	5.45	1.83%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	6.04	12.90%
Stope tonnes above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	4.17	-22.09%

Table A-XXI. Doornkop AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	7.47	
AMG above break-even grade with no royalty costs	7.30	-2.22%
AMG above profit-optimised cut-off grade with 0% royalty rate	7.22	-3.29%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	7.23	-3.12%
AMG above profit-optimised cut-off grade with previous royalty costs	7.32	-1.96%
AMG above profit-optimised cut-off grade with estimated royalty rate	7.33	-1.87%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	7.43	-0.52%
AMG above profit-optimised cut-off grade with variable royalty rate	7.20	-3.53%
AMG above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	7.98	6.92%

Table A-XXII. Doornkop profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$358.72	
Profit with break-even grade with no royalty costs	$361.28	0.71%
Profit with profit-optimised cut-off grade with 0% royalty rate	$361.68	0.83%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$361.66	0.82%
Profit with profit-optimised cut-off grade with previous royalty costs	$361.09	0.66%
Profit with profit-optimised cut-off grade with estimated royalty rate	$361.01	0.64%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$359.52	0.22%
Profit with profit-optimised cut-off grade with variable royalty rate	$361.68	0.83%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$338.14	-5.74%

Table A-XXIII. Doornkop NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	\$225.72	
$NPV_{12\%}$ with break-even grade with no royalty costs	\$220.72	-2.22%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	\$217.70	-3.56%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	\$218.20	-3.33%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	\$221.40	-1.92%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	\$221.64	-1.81%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	\$224.77	-0.42%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	\$217.02	-3.86%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	\$231.66	2.63%

A2.2 Driefontein Consolidated Analysis

Table A-XXIV. Driefontein Consolidated break-even and cut-off grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	8.75	
Break-even grade with no royalty costs	8.15	-6.86%
Profit-optimised cut-off grade with 0% royalty rate	7.97	-8.91%
Profit-optimised cut-off grade with 0.5% royalty rate	8.01	-8.46%
Profit-optimised cut-off grade with previous royalty costs	8.24	-5.83%
Profit-optimised cut-off grade with estimated royalty rate	8.31	-5.03%
Profit-optimised cut-off grade with 5.0% royalty rate	8.31	-5.03%
Profit-optimised cut-off grade with variable royalty rate	7.97	-8.91%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	12.04	37.63%

Table A-XXV. Driefontein Consolidated stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	15.30	
Stope tonnes above break-even grade with no royalty costs	17.39	13.66%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	18.07	18.11%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	17.88	16.88%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	17.17	12.18%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	16.82	9.89%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	16.82	9.89%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	18.07	18.11%
Stope tonnes above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	8.35	-45.46%

Table A-XXVI. Driefontein Consolidated AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	14.98	
AMG above break-even grade with no royalty costs	14.20	-5.25%
AMG above profit-optimised cut-off grade with 0% royalty rate	13.97	-6.80%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	14.03	-6.38%
AMG above profit-optimised cut-off grade with previous royalty costs	14.28	-4.73%
AMG above profit-optimised cut-off grade with estimated royalty rate	14.40	-3.89%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	14.40	-3.89%
AMG above profit-optimised cut-off grade with variable royalty rate	13.97	-6.80%
AMG above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	18.93	26.34%

Table A-XXVII. Driefontein Consolidated profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$3,175.11	
Profit with break-even grade with no royalty costs	$3,203.59	0.90%
Profit with profit-optimised cut-off grade with 0% royalty rate	$3,205.14	0.95%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$3,205.05	0.94%
Profit with profit-optimised cut-off grade with previous royalty costs	$3,202.10	0.85%
Profit with profit-optimised cut-off grade with estimated royalty rate	$3,199.00	0.75%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$3,199.00	0.75%
Profit with profit-optimised cut-off grade with variable royalty rate	$3,205.14	0.95%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$2,932.82	-7.63%

Table A-XXVIII. Driefontein Consolidated NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	$1,579.36	
$NPV_{12\%}$ with break-even grade with no royalty costs	$1,478.83	-6.37%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	$1,445.17	-8.50%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	$1,454.83	-7.88%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	$1,489.88	-5.67%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	$1,507.30	-4.56%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	$1,507.30	-4.56%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	$1,445.17	-8.50%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$1,911.83	21.05%

A2.3 Kloof Consolidated Analysis

Table A-XXIX. Kloof Consolidated break-even and cut-off grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	8.85	
Break-even grade with no royalty costs	8.49	-4.07%
Profit-optimised cut-off grade with 0% royalty rate	8.28	-6.44%
Profit-optimised cut-off grade with 0.5% royalty rate	8.32	-5.99%
Profit-optimised cut-off grade with previous royalty costs	8.59	-2.94%
Profit-optimised cut-off grade with estimated royalty rate	8.53	-3.62%
Profit-optimised cut-off grade with 5.0% royalty rate	8.70	-1.69%
Profit-optimised cut-off grade with variable royalty rate	8.30	-6.18%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	11.43	29.17%

Table A-XXX. Kloof Consolidated stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	30.91	
Stope tonnes above break-even grade with no royalty costs	33.17	7.33%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	35.01	13.27%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	34.62	12.03%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	32.73	5.91%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	32.98	6.72%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	31.99	3.51%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	34.77	12.51%
Stope tonnes above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	16.44	-46.80%

Table A-XXXI. Kloof Consolidated AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	12.47	
AMG above break-even grade with no royalty costs	12.21	-2.07%
AMG above profit-optimised cut-off grade with 0% royalty rate	12.01	-3.69%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	12.05	-3.35%
AMG above profit-optimised cut-off grade with previous royalty costs	12.26	-1.68%
AMG above profit-optimised cut-off grade with estimated royalty rate	12.23	-1.90%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	12.34	-1.01%
AMG above profit-optimised cut-off grade with variable royalty rate	12.04	-3.48%
AMG above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	14.59	17.03%

Table A-XXXII. Kloof Consolidated profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$3,853.15	
Profit with break-even grade with no royalty costs	$3,878.86	0.67%
Profit with profit-optimised cut-off grade with 0% royalty rate	$3,883.27	0.78%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$3,883.34	0.78%
Profit with profit-optimised cut-off grade with previous royalty costs	$3,875.75	0.59%
Profit with profit-optimised cut-off grade with estimated royalty rate	$3,877.68	0.64%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$3,868.34	0.39%
Profit with profit-optimised cut-off grade with variable royalty rate	$3,883.37	0.78%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$3,094.38	-19.69%

Table A-XXXIII. Kloof Consolidated NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	$1,403.68	
$NPV_{12\%}$ with break-even grade with no royalty costs	$1,338.74	-4.63%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	$1,284.37	-8.50%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	$1,295.82	-7.68%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	$1,351.58	-3.71%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	$1,344.31	-4.23%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	$1,372.84	-2.20%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	$1,291.35	-8.00%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$1,670.40	19.00%

A2.4 Kusasalethu Analysis

Table A-XXXIV. Kusasalethu break-even and cut-off grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	6.99	
Break-even grade with no royalty costs	6.74	-3.58%
Profit-optimised cut-off grade with 0% royalty rate	6.58	-5.87%
Profit-optimised cut-off grade with 0.5% royalty rate	6.58	-5.87%
Profit-optimised cut-off grade with previous royalty costs	6.73	-3.72%
Profit-optimised cut-off grade with estimated royalty rate	6.76	-3.29%
Profit-optimised cut-off grade with 5.0% royalty rate	6.91	-1.14%
Profit-optimised cut-off grade with variable royalty rate	6.60	-5.60%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	8.39	20.07%

Table A-XXXV. Kusasalethu stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	9.59	
Stope tonnes above break-even grade with no royalty costs	10.11	5.34%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	10.49	9.33%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	10.49	9.33%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	10.14	5.66%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	10.07	4.96%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	9.70	1.08%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	10.43	8.74%
Stope tonnes above NPV12% optimised cut-off grade with variable royalty rate	6.30	-34.32%

Table A-XXXVI. Kusasalethu AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	9.45	
AMG above break-even grade with no royalty costs	9.32	-1.40%
AMG above profit-optimised cut-off grade with 0% royalty rate	9.23	-2.42%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	9.23	-2.42%
AMG above profit-optimised cut-off grade with previous royalty costs	9.32	-1.48%
AMG above profit-optimised cut-off grade with estimated royalty rate	9.33	-1.30%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	9.43	-0.28%
AMG above profit-optimised cut-off grade with variable royalty rate	9.24	-2.27%
AMG above NPV12% optimised cut-off grade with variable royalty rate	10.39	9.89%

Table A-XXXVII. Kusasalethu profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$804.95	
Profit with break-even grade with no royalty costs	$808.83	0.48%
Profit with profit-optimised cut-off grade with 0% royalty rate	$809.55	0.57%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$809.55	0.57%
Profit with profit-optimised cut-off grade with previous royalty costs	$808.95	0.50%
Profit with profit-optimised cut-off grade with estimated royalty rate	$808.67	0.46%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$806.00	0.13%
Profit with profit-optimised cut-off grade with variable royalty rate	$809.56	0.57%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$701.63	-12.84%

Table A-XXXVIII. Kusasalethu NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	\$344.58	
$NPV_{12\%}$ with break-even grade with no royalty costs	\$334.42	-2.95%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	\$326.34	-5.29%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	\$326.34	-5.29%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	\$333.79	-3.13%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	\$335.18	-2.73%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	\$342.60	-0.57%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	\$327.54	-4.94%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	\$382.02	10.87%

A2.5 Mponeng Analysis

Table A-XXXIX. Mponeng break-even and cut-off Grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	8.49	
Break-even grade with no royalty costs	8.00	-5.77%
Profit-optimised cut-off grade with 0% royalty rate	7.80	-8.13%
Profit-optimised cut-off grade with 0.5% royalty rate	7.84	-7.66%
Profit-optimised cut-off grade with previous royalty costs	8.07	-4.95%
Profit-optimised cut-off grade with estimated royalty rate	8.10	-4.59%
Profit-optimised cut-off grade with 5.0% royalty rate	8.20	-3.42%
Profit-optimised cut-off grade with variable royalty rate	7.82	-7.85%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	14.11	66.22%

Table A-XL. Mponeng stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	19.12	
Stope tonnes above break-even grade with no royalty costs	20.02	4.69%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	20.50	7.20%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	20.44	6.89%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	19.91	4.13%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	19.86	3.87%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	19.74	3.21%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	20.46	6.99%
Stope tonnes above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	6.77	-64.60%

Table A-XLI. Mponeng AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	13.72	
AMG above break-even grade with no royalty costs	13.47	-1.78%
AMG above profit-optimised cut-off grade with 0% royalty rate	13.34	-2.73%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	13.36	-2.61%
AMG above profit-optimised cut-off grade with previous royalty costs	13.50	-1.56%
AMG above profit-optimised cut-off grade with estimated royalty rate	13.52	-1.47%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	13.55	-1.22%
AMG above profit-optimised cut-off grade with variable royalty rate	13.36	-2.65%
AMG above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	18.52	34.99%

Table A-XLII. Mponeng profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$3,213.41	
Profit with break-even grade with no royalty costs	$3,224.75	0.35%
Profit with profit-optimised cut-off grade with 0% royalty rate	$3,225.81	0.39%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$3,225.81	0.39%
Profit with profit-optimised cut-off grade with previous royalty costs	$3,224.10	0.33%
Profit with profit-optimised cut-off grade with estimated royalty rate	$3,223.73	0.32%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$3,222.55	0.28%
Profit with profit-optimised cut-off grade with variable royalty rate	$3,225.82	0.39%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$2,236.45	-30.40%

Table A-XLIII. Mponeng NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	$668.61	
$NPV_{12\%}$ with break-even grade with no royalty costs	$642.30	-3.94%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	$628.08	-6.06%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	$629.84	-5.80%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	$645.50	-3.46%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	$646.93	-3.24%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	$650.65	-2.69%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	$629.29	-5.88%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$1,058.05	58.25%

A2.6 Moab Khotsong Analysis

Table A-XLIV. Moab Khotsong break-even and cut-off grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	8.27	
Break-even grade with no royalty costs	7.75	-6.29%
Profit-optimised cut-off grade with 0% royalty rate	7.55	-8.71%
Profit-optimised cut-off grade with 0.5% royalty rate	7.58	-8.34%
Profit-optimised cut-off grade with previous royalty costs	7.70	-6.89%
Profit-optimised cut-off grade with estimated royalty rate	7.82	-5.44%
Profit-optimised cut-off grade with 5.0% royalty rate	7.95	-3.87%
Profit-optimised cut-off grade with variable royalty rate	7.58	-8.34%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	12.61	52.46%

Table A-XLV. Moab Khotsong stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	17.43	
Stope tonnes above break-even grade with no royalty costs	17.60	0.95%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	17.67	1.38%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	17.66	1.29%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	17.60	0.98%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	17.60	0.95%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	17.58	0.84%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	17.66	1.29%
Stope tonnes above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	11.40	-34.61%

Table A-XLVI. Moab Khotsong AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	13.96	
AMG above break-even grade with no royalty costs	13.90	-0.40%
AMG above profit-optimised cut-off grade with 0% royalty rate	13.88	-0.59%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	13.88	-0.54%
AMG above profit-optimised cut-off grade with previous royalty costs	13.90	-0.41%
AMG above profit-optimised cut-off grade with estimated royalty rate	13.90	-0.40%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	13.91	-0.35%
AMG above profit-optimised cut-off grade with variable royalty rate	13.88	-0.54%
AMG above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	15.62	11.89%

Table A-XLVII. Moab Khotsong profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$2,910.00	
Profit with break-even grade with no royalty costs	$2,912.30	0.08%
Profit with profit-optimised cut-off grade with 0% royalty rate	$2,912.44	0.08%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$2,912.45	0.08%
Profit with profit-optimised cut-off grade with previous royalty costs	$2,912.32	0.08%
Profit with profit-optimised cut-off grade with estimated royalty rate	$2,912.30	0.08%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$2,912.14	0.07%
Profit with profit-optimised cut-off grade with variable royalty rate	$2,912.45	0.08%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$2,397.35	-17.62%

Table A-XLVIII. Moab Khotsong NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	$933.86	
$NPV_{12\%}$ with break-even grade with no royalty costs	$927.38	-0.69%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	$924.22	-1.03%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	$924.93	-0.96%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	$927.21	-0.71%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	$927.38	-0.69%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	$928.22	-0.60%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	$924.93	-0.96%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$1,049.13	12.34%

A2.7 Bambanani Analysis

Table A-XLIX. Bambanani break-even and cut-off grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	8.29	
Break-even grade with no royalty costs	8.03	-3.14%
Profit-optimised cut-off grade with 0% royalty rate	7.84	-5.38%
Profit-optimised cut-off grade with 0.5% royalty rate	7.87	-5.07%
Profit-optimised cut-off grade with previous royalty costs	8.03	-3.14%
Profit-optimised cut-off grade with estimated royalty rate	8.03	-3.14%
Profit-optimised cut-off grade with 5.0% royalty rate	8.23	-0.72%
Profit-optimised cut-off grade with variable royalty rate	7.84	-5.38%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	8.06	-2.81%

Table A-L. Bambanani stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	0.30	
Stope tonnes above break-even grade with no royalty costs	0.31	5.20%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	0.33	9.67%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	0.32	9.29%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	0.31	5.20%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	0.31	5.20%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	0.30	1.86%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	0.33	9.67%
Stope tonnes above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	0.31	5.02%

Table A-LI. Bambanani AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	10.88	
AMG above break-even grade with no royalty costs	10.75	-1.23%
AMG above profit-optimised cut-off grade with 0% royalty rate	10.63	-2.28%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	10.64	-2.19%
AMG above profit-optimised cut-off grade with previous royalty costs	10.75	-1.23%
AMG above profit-optimised cut-off grade with estimated royalty rate	10.75	-1.23%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	10.83	-0.44%
AMG above profit-optimised cut-off grade with variable royalty rate	10.63	-2.28%
AMG above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	10.75	-1.19%

Table A-LII. Bambanani profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$26.34	
Profit with break-even grade with no royalty costs	$26.48	0.55%
Profit with profit-optimised cut-off grade with 0% royalty rate	$26.51	0.67%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$26.51	0.67%
Profit with profit-optimised cut-off grade with previous royalty costs	$26.48	0.55%
Profit with profit-optimised cut-off grade with estimated royalty rate	$26.48	0.55%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$26.40	0.25%
Profit with profit-optimised cut-off grade with variable royalty rate	$26.51	0.67%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$26.48	0.54%

Table A-LIII. Bambanani NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	\$22.64	
$NPV_{12\%}$ with break-even grade with no royalty costs	\$22.68	0.19%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	\$22.65	0.03%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	\$22.65	0.05%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	\$22.68	0.19%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	\$22.68	0.19%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	\$22.67	0.12%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	\$22.65	0.03%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	\$22.68	0.19%

A2.8 Beatrix Analysis

Table A-LIV. Beatrix break-even and cut-off grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	5.48	
Break-even grade with no royalty costs	5.28	-3.65%
Profit-optimised cut-off grade with 0% royalty rate	5.14	-6.20%
Profit-optimised cut-off grade with 0.5% royalty rate	5.17	-5.66%
Profit-optimised cut-off grade with previous royalty costs	5.32	-2.92%
Profit-optimised cut-off grade with estimated royalty rate	5.29	-3.47%
Profit-optimised cut-off grade with 5.0% royalty rate	5.41	-1.28%
Profit-optimised cut-off grade with variable royalty rate	5.16	-5.80%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	5.85	6.70%

Table A-LV. Beatrix stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	7.96	
Stope tonnes above break-even grade with no royalty costs	8.75	9.91%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	9.22	15.92%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	9.10	14.40%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	8.57	7.63%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	8.71	9.42%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	8.19	2.87%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	9.13	14.78%
Stope tonnes above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	6.77	-14.89%

Table A-LVI. Beatrix AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	7.57	
AMG above break-even grade with no royalty costs	7.37	-2.61%
AMG above profit-optimised cut-off grade with 0% royalty rate	7.26	-4.09%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	7.28	-3.72%
AMG above profit-optimised cut-off grade with previous royalty costs	7.41	-2.03%
AMG above profit-optimised cut-off grade with estimated royalty rate	7.38	-2.49%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	7.51	-0.78%
AMG above profit-optimised cut-off grade with variable royalty rate	7.28	-3.82%
AMG above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	7.90	4.41%

Table A-LVII. Beatrix profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$478.06	
Profit with break-even grade with no royalty costs	$482.24	0.88%
Profit with profit-optimised cut-off grade with 0% royalty rate	$482.79	0.99%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$482.81	0.99%
Profit with profit-optimised cut-off grade with previous royalty costs	$481.61	0.74%
Profit with profit-optimised cut-off grade with estimated royalty rate	$482.12	0.85%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$479.68	0.34%
Profit with profit-optimised cut-off grade with variable royalty rate	$482.81	0.99%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$463.40	-3.07%

Table A-LVIII. Beatrix NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	$348.48	
$NPV_{12\%}$ with break-even grade with no royalty costs	$343.25	-1.50%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	$338.51	-2.86%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	$339.77	-2.50%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	$344.89	-1.03%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	$343.61	-1.40%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	$347.50	-0.28%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	$339.45	-2.59%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$350.89	0.69%

A2.9 Joel Analysis

Table A-LIX. Joel break-even and cut-off grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	4.91	
Break-even grade with no royalty costs	4.70	-4.28%
Profit-optimised cut-off grade with 0% royalty rate	4.58	-6.72%
Profit-optimised cut-off grade with 0.5% royalty rate	4.61	-6.11%
Profit-optimised cut-off grade with previous royalty costs	4.71	-4.07%
Profit-optimised cut-off grade with estimated royalty rate	4.73	-3.67%
Profit-optimised cut-off grade with 5.0% royalty rate	4.82	-1.83%
Profit-optimised cut-off grade with variable royalty rate	4.61	-6.18%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	6.23	26.87%

Table A-LX. Joel stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	5.66	
Stope tonnes above break-even grade with no royalty costs	5.89	4.09%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	6.00	6.10%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	5.98	5.65%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	5.89	4.02%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	5.86	3.57%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	5.73	1.34%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	5.98	5.73%
Stope tonnes above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	3.84	-32.14%

Table A-LXI. Joel AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	7.09	
AMG above break-even grade with no royalty costs	7.00	-1.27%
AMG above profit-optimised cut-off grade with 0% royalty rate	6.95	-1.90%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	6.96	-1.76%
AMG above profit-optimised cut-off grade with previous royalty costs	7.00	-1.25%
AMG above profit-optimised cut-off grade with estimated royalty rate	7.01	-1.11%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	7.06	-0.42%
AMG above profit-optimised cut-off grade with variable royalty rate	6.96	-1.79%
AMG above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	7.79	9.92%

Table A-LXII. Joel profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$399.21	
Profit with break-even grade with no royalty costs	$400.49	0.32%
Profit with profit-optimised cut-off grade with 0% royalty rate	$400.62	0.35%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$400.62	0.35%
Profit with profit-optimised cut-off grade with previous royalty costs	$400.47	0.32%
Profit with profit-optimised cut-off grade with estimated royalty rate	$400.39	0.29%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$399.77	0.14%
Profit with profit-optimised cut-off grade with variable royalty rate	$400.62	0.35%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$347.39	-12.98%

Table A-LXIII. Joel NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	\$165.79	
$NPV_{12\%}$ with break-even grade with no royalty costs	\$161.83	-2.39%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	\$159.72	-3.66%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	\$160.20	-3.37%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	\$161.90	-2.35%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	\$162.34	-2.08%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	\$164.52	-0.77%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	\$160.13	-3.42%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	\$181.81	9.66%

A2.10 Masimong Analysis

Table A-LXIV. Masimong break-even and cut-off grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	6.43	
Break-even grade with no royalty costs	6.25	-2.80%
Profit-optimised cut-off grade with 0% royalty rate	6.10	-5.13%
Profit-optimised cut-off grade with 0.5% royalty rate	6.13	-4.67%
Profit-optimised cut-off grade with previous royalty costs	6.27	-2.49%
Profit-optimised cut-off grade with estimated royalty rate	6.24	-2.95%
Profit-optimised cut-off grade with 5.0% royalty rate	6.41	-0.31%
Profit-optimised cut-off grade with variable royalty rate	6.11	-4.93%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	6.34	-1.41%

Table A-LXV. Masimong stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	1.31	
Stope tonnes above break-even grade with no royalty costs	1.37	4.30%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	1.43	9.14%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	1.41	7.53%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	1.36	3.76%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	1.37	4.57%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	1.32	0.54%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	1.42	8.33%
Stope tonnes above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	1.34	2.42%

Table A-LXVI. Masimong AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	8.13	
AMG above break-even grade with no royalty costs	8.06	-0.90%
AMG above profit-optimised cut-off grade with 0% royalty rate	7.98	-1.93%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	8.00	-1.59%
AMG above profit-optimised cut-off grade with previous royalty costs	8.07	-0.79%
AMG above profit-optimised cut-off grade with estimated royalty rate	8.06	-0.96%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	8.12	-0.11%
AMG above profit-optimised cut-off grade with variable royalty rate	7.99	-1.76%
AMG above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	8.09	-0.50%

Table A-LXVII. Masimong profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$51.58	
Profit with break-even grade with no royalty costs	$51.84	0.51%
Profit with profit-optimised cut-off grade with 0% royalty rate	$51.92	0.64%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$51.91	0.64%
Profit with profit-optimised cut-off grade with previous royalty costs	$51.82	0.47%
Profit with profit-optimised cut-off grade with estimated royalty rate	$51.85	0.52%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$51.63	0.08%
Profit with profit-optimised cut-off grade with variable royalty rate	$51.92	0.64%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$51.76	0.34%

Table A-LXVIII. Masimong NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	$41.58	
$NPV_{12\%}$ with break-even grade with no royalty costs	$41.59	0.02%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	$41.33	-0.60%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	$41.46	-0.30%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	$41.60	0.04%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	$41.59	0.01%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	$41.59	0.02%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	$41.39	-0.45%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$41.61	0.06%

A2.11 Tshepong Analysis

Table A-LXIX. Tshepong break-even and cut-off grades

Approach	Grade (g/t)	% Diff
Base case Break-even grade with estimated royalty rate	6.19	
Break-even grade with no royalty costs	5.79	-6.46%
Profit-optimised cut-off grade with 0% royalty rate	5.65	-8.72%
Profit-optimised cut-off grade with 0.5% royalty rate	5.68	-8.24%
Profit-optimised cut-off grade with previous royalty costs	5.85	-5.49%
Profit-optimised cut-off grade with estimated royalty rate	5.88	-5.01%
Profit-optimised cut-off grade with 5.0% royalty rate	5.94	-4.04%
Profit-optimised cut-off grade with variable royalty rate	5.67	-8.48%
$NPV_{12\%}$ optimised cut-off grade with variable royalty rate	10.66	72.21%

Table A-LXX. Tshepong stope tonnes above break-even/cut-off grade

Approach	Tonnes (Million)	% Diff
Base case Stope tonnes above break-even grade with estimated royalty rate	31.32	
Stope tonnes above break-even grade with no royalty costs	32.61	4.12%
Stope tonnes above profit-optimised cut-off grade with 0% royalty rate	33.01	5.39%
Stope tonnes above profit-optimised cut-off grade with 0.5% royalty rate	32.92	5.11%
Stope tonnes above profit-optimised cut-off grade with previous royalty costs	32.45	3.60%
Stope tonnes above profit-optimised cut-off grade with estimated royalty rate	32.34	3.26%
Stope tonnes above profit-optimised cut-off grade with 5.0% royalty rate	32.14	2.61%
Stope tonnes above profit-optimised cut-off grade with variable royalty rate	32.95	5.20%
Stope tonnes above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	13.21	-57.84%

Table A-LXXI. Tshepong AMG

Approach	Grade (g/t)	% Diff
Base case AMG above break-even grade with estimated royalty rate	10.47	
AMG above break-even grade with no royalty costs	10.30	-1.69%
AMG above profit-optimised cut-off grade with 0% royalty rate	10.24	-2.22%
AMG above profit-optimised cut-off grade with 0.5% royalty rate	10.25	-2.10%
AMG above profit-optimised cut-off grade with previous royalty costs	10.32	-1.48%
AMG above profit-optimised cut-off grade with estimated royalty rate	10.33	-1.34%
AMG above profit-optimised cut-off grade with 5.0% royalty rate	10.36	-1.07%
AMG above profit-optimised cut-off grade with variable royalty rate	10.25	-2.14%
AMG above $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	13.25	26.48%

Table A-LXXII. Tshepong profit after royalties and tax

Approach	Profit (Million)	% Diff
Base case Profit with break-even grade with estimated royalty rate	$3,751.91	
Profit with break-even grade with no royalty costs	$3,762.35	0.28%
Profit with profit-optimised cut-off grade with 0% royalty rate	$3,762.89	0.29%
Profit with profit-optimised cut-off grade with 0.5% royalty rate	$3,762.90	0.29%
Profit with profit-optimised cut-off grade with previous royalty costs	$3,761.73	0.26%
Profit with profit-optimised cut-off grade with estimated royalty rate	$3,761.20	0.25%
Profit with profit-optimised cut-off grade with 5.0% royalty rate	$3,759.98	0.22%
Profit with profit-optimised cut-off grade with variable royalty rate	$3,762.90	0.29%
Profit with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$2,703.12	-27.95%

Table A-LXXIII. Tshepong NPV

Approach	$NPV_{12\%}$ (Million)	% Diff
Base case $NPV_{12\%}$ with break-even grade with estimated royalty rate	$1,201.85	
$NPV_{12\%}$ with break-even grade with no royalty costs	$1,165.88	-2.99%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0% royalty rate	$1,154.44	-3.95%
$NPV_{12\%}$ with profit-optimised cut-off grade with 0.5% royalty rate	$1,156.93	-3.74%
$NPV_{12\%}$ with profit-optimised cut-off grade with previous royalty costs	$1,170.55	-2.60%
$NPV_{12\%}$ with profit-optimised cut-off grade with estimated royalty rate	$1,173.63	-2.35%
$NPV_{12\%}$ with profit-optimised cut-off grade with 5.0% royalty rate	$1,179.47	-1.86%
$NPV_{12\%}$ with profit-optimised cut-off grade with variable royalty rate	$1,156.13	-3.80%
$NPV_{12\%}$ with $NPV_{12\%}$ optimised cut-off grade with variable royalty rate	$1,507.30	25.41%

APPENDIX 3 MULTIPLE-CRITERIA CUT-OFF GRADE ANALYSIS

Table A-LXXIV. Doornkop multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	5.00	6.24	3.84	1.97	4.26
Stope Tonnes	Mt	6.05	3.78	7.96	9.00	7.31
Milled Tonnes	Mt	7.42	4.63	9.75	11.04	8.96
LoM	years	9	6	12	13	11
AMG	g/t	7.20	8.18	6.54	6.16	6.76
Profit	US$ (m)	$362	$326	$332	$282	$349
$NPV_{12\%}$	US$ (m)	$217	$230	$176	$140	$192
Royalty Rate	%	2.81%	3.49%	2.24%	1.85%	2.44%
Gold Tax Rate	%	27.49%	28.99%	25.28%	22.69%	26.22%
Total Revenue	US$ (m)	$1,911	$1,355	$2,281	$2,431	$2,166
Total Mining Costs	US$ (m)	($1,359)	($848)	($1,785)	($2,021)	($1,640)
Total Royalties	US$ (m)	($54)	($47)	($51)	($45)	($53)
Total Income Tax	US$ (m)	($137)	($133)	($112)	($83)	($124)
Total Tax Contribution	US$ (m)	($406)	($327)	($428)	($416)	($426)

Figure A-20. Doornkop multiple-criteria cut-off grade graph.

Table A-LXXV. Driefontein Consolidated multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	7.97	12.04	6.16	0.88	6.76
Stope Tonnes	Mt	18.07	8.35	24.29	34.43	21.92
Milled Tonnes	Mt	22.35	10.33	30.05	42.58	27.12
LoM	years	16	8	21	29	19
AMG	g/t	13.97	18.93	12.19	10.01	12.81
Profit	US$ (m)	$3,205	$2,933	$3,032	$2,080	$3,138
$NPV_{12\%}$	US$ (m)	$1,445	$1,912	$1,116	$577	$1,245
Royalty Rate	%	3.83%	0.50%	3.15%	1.99%	3.41%
Gold Tax Rate	%	29.50%	30.99%	28.33%	23.76%	28.84%
Total Revenue	US$ (m)	$12,031	$7,533	$14,115	$16,434	$13,387
Total Mining Costs	US$ (m)	($7,024)	($3,245)	($9,441)	($13,380)	($8,521)
Total Royalties	US$ (m)	($461)	($38)	($445)	($326)	($456)
Total Income Tax	US$ (m)	($1,341)	($1,317)	($1,198)	($648)	($1,272)
Total Tax Contribution	US$ (m)	($3,053)	($2,081)	($3,170)	($2,871)	($3,155)

Figure A-21. Driefontein Cons multiple-criteria cut-off grade graph.

Table A-LXXVI. Kloof Consolidated multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	8.30	11.43	6.48	5.26	7.87
Stope Tonnes	Mt	34.80	16.45	46.82	53.81	37
Milled Tonnes	Mt	43.34	20.49	58.31	67.03	47
LoM	years	24	12	32	36	26
AMG	g/t	12.03	14.59	10.83	9.83	11.75
Profit	US$ (m)	$3,883	$3,095	$3,537	$2,466	$3,867
$NPV_{12\%}$	US$ (m)	$1,291	$1,670	$914	$561	$1,211
Royalty Rate	%	2.86%	3.85%	2.23%	1.59%	2.72%
Gold Tax Rate	%	27.61%	29.52%	25.22%	19.92%	27.21%
Total Revenue	US$ (m)	$20,175	$11,564	$24,425	$25,501	$21,210
Total Mining Costs	US$ (m)	($14,235)	($6,728)	($19,152)	($22,015)	($15,320)
Total Royalties	US$ (m)	($576)	($445)	($544)	($406)	($577)
Total Income Tax	US$ (m)	($1,481)	($1,296)	($1,193)	($613)	($1,446)
Total Tax Contribution	US$ (m)	($4,227)	($2,919)	($4,453)	($3,949)	($4,321)

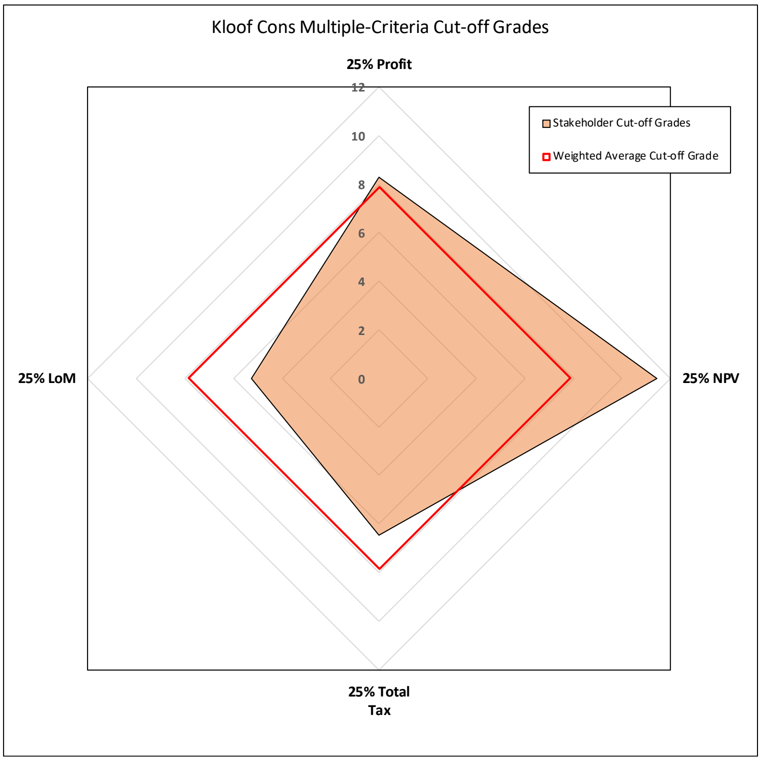

Figure A-22. Kloof Cons multiple-criteria cut-off grade graph.

Table A-LXXVII. Kusasalethu multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	6.60	8.38	5.10	2.40	5.62
Stope Tonnes	Mt	10.42	6.32	13.52	15.82	12.33
Milled Tonnes	Mt	12.64	7.67	16.40	19.19	14.96
LoM	years	18	11	24	28	22
AMG	g/t	9.24	10.38	8.46	7.82	8.76
Profit	US$ (m)	$810	$703	$741	$568	$784
$NPV_{12\%}$	US$ (m)	$328	$382	$247	$167	$281
Royalty Rate	%	2.66%	3.30%	2.12%	1.60%	2.34%
Gold Tax Rate	%	27.02%	28.64%	24.65%	20.01%	25.78%
Total Revenue	US$ (m)	$4,552	$3,103	$5,408	$5,847	$5,107
Total Mining Costs	US$ (m)	($3,322)	($2,015)	($4,310)	($5,043)	($3,931)
Total Royalties	US$ (m)	($121)	($102)	($115)	($94)	($120)
Total Income Tax	US$ (m)	($300)	($282)	($242)	($142)	($272)
Total Tax Contribution	US$ (m)	($927)	($717)	($977)	($924)	($970)

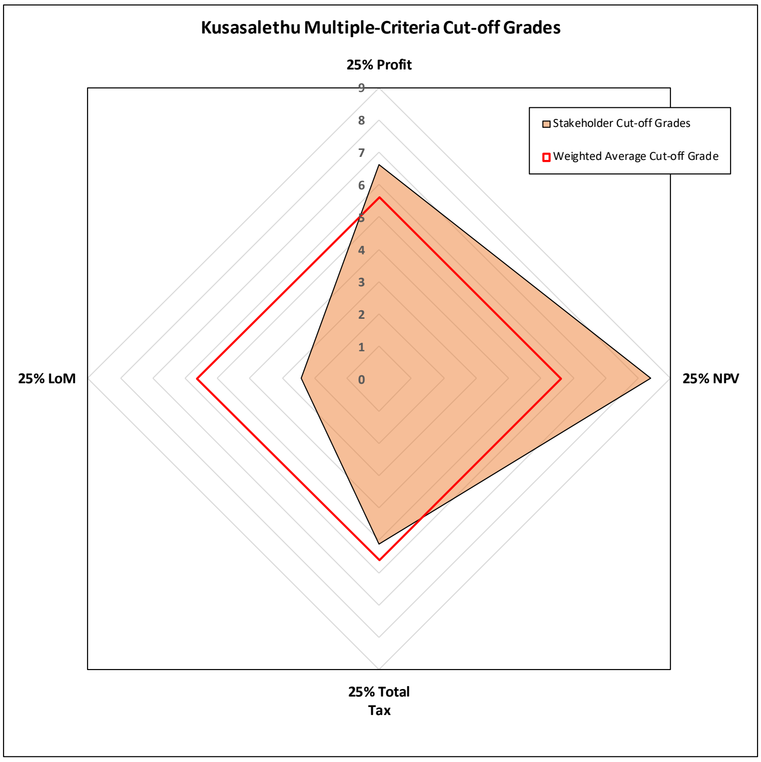

Figure A-23. Kusasalethu multiple-criteria cut-off grade graph.

Table A-LXXVIII. Mponeng multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	7.83	14.09	6.25	3.26	7.86
Stope Tonnes	Mt	20.45	6.77	23.20	24.14	20.34
Milled Tonnes	Mt	28.93	9.57	32.82	34.15	28.76
LoM	years	43	15	49	50	43
AMG	g/t	13.36	18.52	12.62	12.21	13.39
Profit	US$ (m)	$3,226	$2,236	$3,170	$3,020	$3,226
$NPV_{12\%}$	US$ (m)	$629	$1,058	$547	$502	$633
Royalty Rate	%	3.71%	0.50%	3.43%	3.26%	3.72%
Gold Tax Rate	%	29.33%	30.98%	28.87%	28.55%	29.34%
Total Revenue	US$ (m)	$12,548	$5,757	$13,446	$13,543	$12,505
Total Mining Costs	US$ (m)	($7,518)	($2,488)	($8,529)	($8,875)	($7,474)
Total Royalties	US$ (m)	($465)	($29)	($461)	($441)	($465)
Total Income Tax	US$ (m)	($1,339)	($1,004)	($1,286)	($1,207)	($1,340)
Total Tax Contribution	US$ (m)	($3,034)	($1,560)	($3,083)	($3,005)	($3,030)

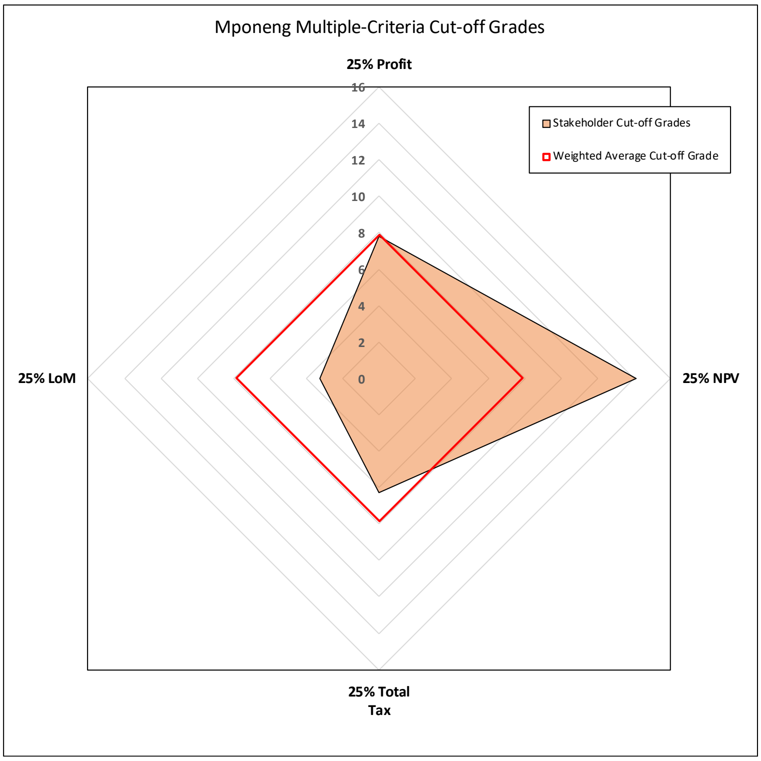

Figure A-24. Mponeng multiple-criteria cut-off grade graph.

Table A-LXXIX. Moab Khotsong multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	7.58	12.62	5.65	1.14	6.75
Stope Tonnes	Mt	17.66	11.40	18.17	18.20	18.00
Milled Tonnes	Mt	22.24	14.36	22.88	22.92	22.67
LoM	years	25	16	26	26	26
AMG	g/t	13.88	15.62	13.69	13.67	13.76
Profit	US$ (m)	$2,912	$2,397	$2,904	$2,902	$2,910
$NPV_{12\%}$	US$ (m)	$925	$1,049	$901	$899	$909
Royalty Rate	%	4.04%	4.53%	3.97%	3.97%	4.00%
Gold Tax Rate	%	29.77%	30.29%	29.69%	29.68%	29.72%
Total Revenue	US$ (m)	$10,324	$7,498	$10,472	$10,479	$10,429
Total Mining Costs	US$ (m)	($5,760)	($3,718)	($5,926)	($5,937)	($5,873)
Total Royalties	US$ (m)	($417)	($340)	($416)	($416)	($417)
Total Income Tax	US$ (m)	($1,234)	($1,042)	($1,226)	($1,225)	($1,230)
Total Tax Contribution	US$ (m)	($2,784)	($2,176)	($2,797)	($2,796)	($2,795)

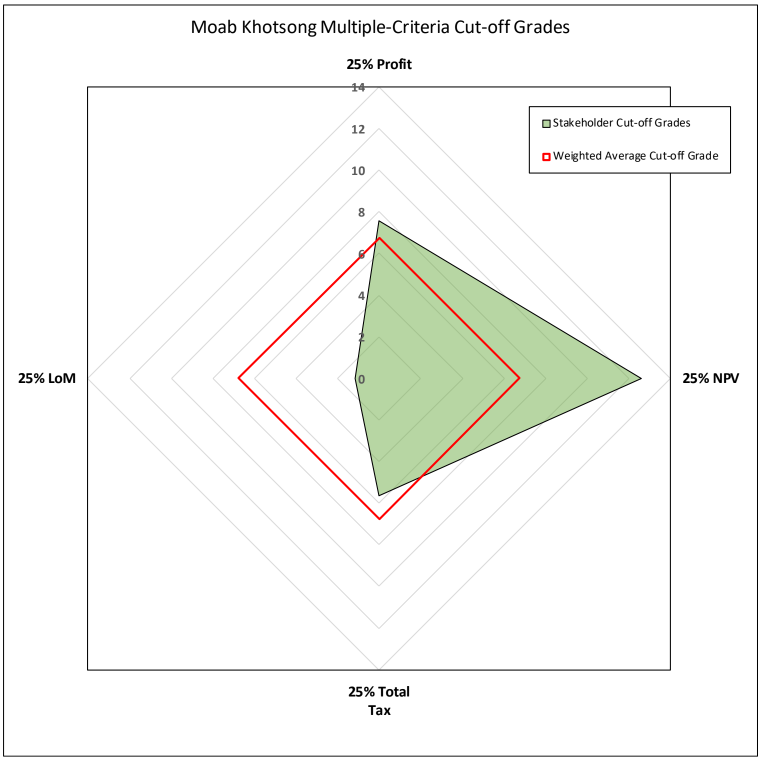

Figure A-25. Moab Khotsong multiple-criteria cut-off grade graph.

Table A-LXXX. Bambanani multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	7.84	8.06	6.21	0.93	5.76
Stope Tonnes	Mt	0.33	0.31	0.39	0.40	0.40
Milled Tonnes	Mt	0.38	0.36	0.45	0.47	0.46
LoM	years	2	2	2	3	3
AMG	g/t	10.63	10.76	10.08	9.95	9.99
Profit	US$ (m)	$27	$26	$25	$24	$25
$NPV_{12\%}$	US$ (m)	$23	$23	$21	$21	$21
Royalty Rate	%	2.45%	2.53%	2.13%	2.04%	2.07%
Gold Tax Rate	%	26.26%	26.54%	24.66%	24.11%	24.31%
Total Revenue	US$ (m)	$164	$158	$184	$188	$187
Total Mining Costs	US$ (m)	($123.7)	($118.1)	($146.8)	($151.6)	($150.1)
Total Royalties	US$ (m)	($4.02)	($3.99)	($3.92)	($3.83)	($3.86)
Total Income Tax	US$ (m)	($9.44)	($9.57)	($8.27)	($7.78)	($7.96)
Total Tax Contribution	US$ (m)	($30.93)	($30.37)	($32.16)	($32.04)	($32.12)

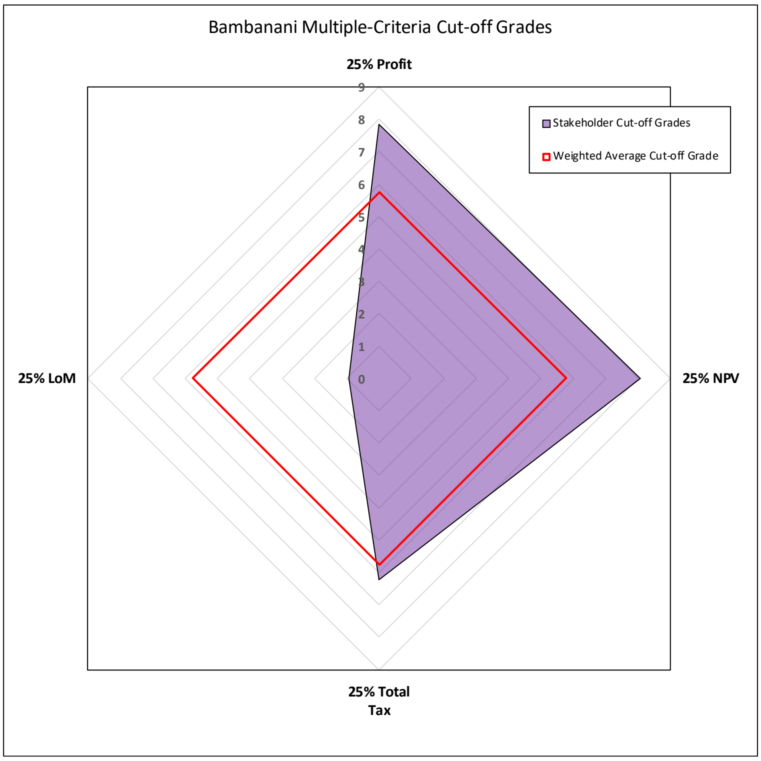

Figure A-26. Bambanani multiple-criteria cut-off grade graph.

Table A-LXXXI. Beatrix multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	5.16	5.85	3.84	3.84	4.67
Stope Tonnes	Mt	9.16	6.77	15.51	15.51	11.17
Milled Tonnes	Mt	9.98	7.38	16.91	16.91	12.18
LoM	years	6	5	10	10	7
AMG	g/t	7.27	7.90	6.12	6.12	6.85
Profit	US$ (m)	$483	$463	$370	$370	$470
$NPV_{12\%}$	US$ (m)	$339	$351	$216	$216	$311
Royalty Rate	%	2.69%	3.15%	1.59%	1.59%	2.33%
Gold Tax Rate	%	27.12%	28.34%	19.94%	19.94%	25.73%
Total Revenue	US$ (m)	$2,680	$2,153	$3,819	$3,819	$3,078
Total Mining Costs	US$ (m)	($1,946)	($1,438)	($3,296)	($3,296)	($2,373)
Total Royalties	US$ (m)	($72)	($68)	($61)	($61)	($72)
Total Income Tax	US$ (m)	($180)	($183)	($92)	($92)	($163)
Total Tax Contribution	US$ (m)	($546)	($481)	($596)	($596)	($579)

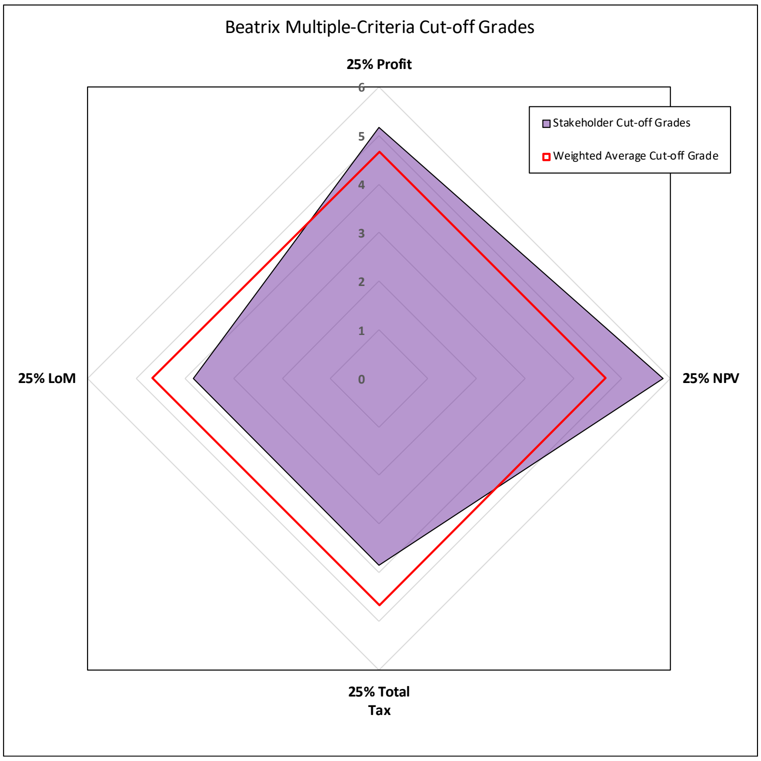

Figure A-27. Beatrix multiple-criteria cut-off grade graph.

Table A-LXXXII. Joel multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	4.61	6.23	3.52	1.46	3.96
Stope Tonnes	Mt	5.98	3.84	7.04	7.81	6.64
Milled Tonnes	Mt	6.53	4.19	7.69	8.52	7.24
LoM	years	19	12	22	24	21
AMG	g/t	6.96	7.79	6.53	6.18	6.70
Profit	US$ (m)	$401	$347	$385	$349	$395
$NPV_{12\%}$	US$ (m)	$160	$182	$137	$114	$146
Royalty Rate	%	3.10%	3.67%	2.74%	2.41%	2.88%
Gold Tax Rate	%	28.21%	29.27%	27.26%	26.08%	27.68%
Total Revenue	US$ (m)	$1,900	$1,365	$2,098	$2,201	$2,029
Total Mining Costs	US$ (m)	($1,283)	($824)	($1,512)	($1,675)	($1,424)
Total Royalties	US$ (m)	($59)	($50)	($57)	($53)	($59)
Total Income Tax	US$ (m)	($157)	($144)	($144)	($123)	($151)
Total Tax Contribution	US$ (m)	($426)	($340)	($438)	($429)	($437)

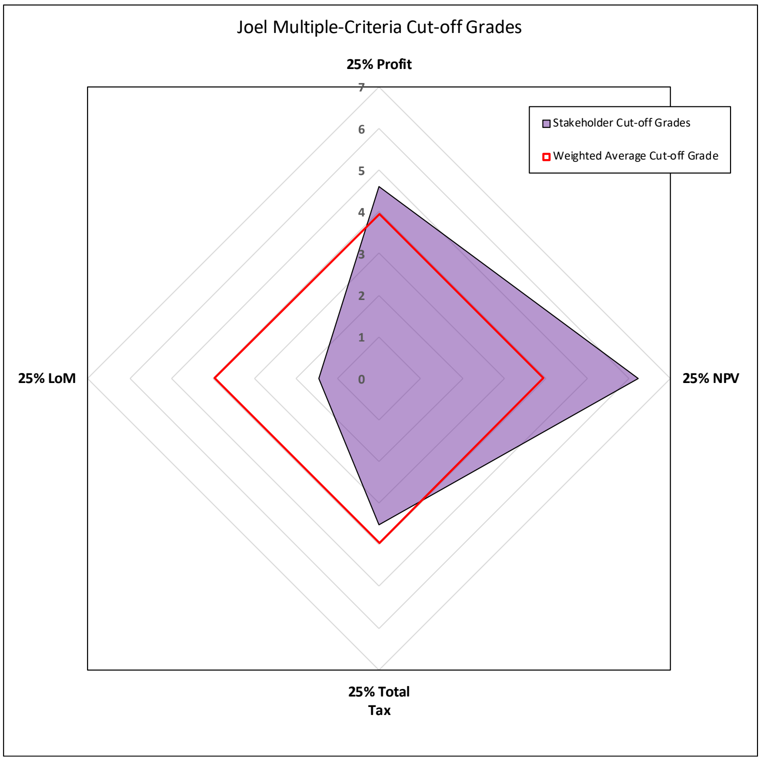

Figure A-28. Joel multiple-criteria cut-off grade graph.

Table A-LXXXIII. Masimong multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	6.11	6.34	4.72	4.60	5.44
Stope Tonnes	Mt	1.43	1.34	1.93	1.99	1.68
Milled Tonnes	Mt	1.57	1.48	2.12	2.18	1.85
LoM	years	4	3	5	5	4
AMG	g/t	7.98	8.09	7.32	7.25	7.65
Profit	US$ (m)	$52	$52	$46	$44	$50
$NPV_{12\%}$	US$ (m)	$41	$42	$34	$33	$39
Royalty Rate	%	2.23%	2.32%	1.67%	1.60%	1.96%
Gold Tax Rate	%	25.26%	25.68%	20.91%	20.03%	23.59%
Total Revenue	US$ (m)	$357	$341	$444	$452	$403
Total Mining Costs	US$ (m)	($280)	($263)	($379)	($390)	($330)
Total Royalties	US$ (m)	($7.98)	($7.91)	($7.42)	($7.24)	($7.92)
Total Income Tax	US$ (m)	($17.54)	($17.89)	($12.05)	($11.01)	($15.53)
Total Tax Contribution	US$ (m)	($66.29)	($64.50)	($71.65)	($71.60)	($70.16)

Figure A-29. Masimong multiple-criteria cut-off grade graph.

Table A-LXXXIV. Tshepong multiple-criteria cut-off grade analysis

Criteria	Units	Profit	NPV	State	LoM	Multi
Cut-off Grades	g/t	5.67	10.66	4.31	1.27	5.48
Stope Tonnes	Mt	32.93	13.20	35.89	37.20	33.45
Milled Tonnes	Mt	39.92	16.00	43.51	45.09	40.55
LoM	years	26	11	28	29	27
AMG	g/t	10.25	13.25	9.82	9.60	10.18
Profit	US$ (m)	$3,763	$2,703	$3,717	$3,649	$3,762
$NPV_{12\%}$	US$ (m)	$1,157	$1,507	$1,062	$1,011	$1,141
Royalty Rate	%	3.98%	0.50%	3.78%	3.67%	3.95%
Gold Tax Rate	%	29.70%	30.95%	29.43%	29.27%	29.65%
Total Revenue	US$ (m)	$13,553	$7,021	$14,152	$14,340	$13,670
Total Mining Costs	US$ (m)	($7,662)	($3,071)	($8,350)	($8,655)	($7,783)
Total Royalties	US$ (m)	($539)	($35)	($535)	($527)	($539)
Total Income Tax	US$ (m)	($1,589)	($1,211)	($1,550)	($1,510)	($1,586)
Total Tax Contribution	US$ (m)	($3,568)	($1,943)	($3,607)	($3,590)	($3,580)

Figure A-30. Tshepong multiple-criteria cut-off grade graph.