Optimizing the cut-off grade for tabular gold deposits, considering the South African gold tax and mineral resource royalty regime

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Abstract

The South African mineral resource royalty system, initiated in 2010, employs a hybrid *ad valorem* approach tied to profitability ratios. This rate is then applied to the total revenue from mineral sales. In this article we explore how the profitability ratio in the mineral resource royalty formulae interacts with the gold tax formula as applied to South African gold mines, devising a strategy for cut-off grade optimization. The study focuses on nine narrow, tabular-reef (Witwatersrand) gold mines.

The approach involves a mixed-integer cut-off grade optimizer utilizing Excel Solver, incorporating relevant royalty and income tax formulae. Different mineral resource royalty cost scenarios were examined. Ignoring these costs in the break-even analysis lowers the cut-off grade but slightly boosts profits compared to considering expected costs. The developed optimizer model, recognizing the profitability aspect of the mineral resource royalty and income tax formulae, yielded a 6% lower cut-off grade than the base case. This is significant for increasing mine life. While the profit differences are marginal (0.2% compared to the break-even base case), substantial improvements were noted: a 6% increase in stope tons above cut-off grade, and a 4% rise in total revenue. Enhanced resource utilization (3% extra gold kilograms) reduces necessary development and overall costs, allowing for a reduction in the cut-off grade and ultimately, more profit.

Keywords

cut-off grade, Excel Solver, mineral resource royalties, gold tax formula, financial optimization, cash flow

Introduction

The cut-off grade determines the mine plan, distinguishing between payable ore, unpayable ore, and waste material (Gholamnejad, 2008). Rising costs, including mineral resource royalties, can increase the cut-off grade and reduce mineable reserves. Limited research exists on how mining taxes and royalties influence cut-off grades and the resulting mineral sterilization, reducing mine life. Ideally, both the company and the State should be satisfied, but this balance is rarely achieved (Lilford, 2017).

If mineral resource royalties were based solely on profit, they could be disregarded for cut-off grade calculations, similar to income tax. However, as they are imposed on total sales, *ad valorem* and mining volume royalties are considered costs in determining the cut-off grade (Hall, 2014). Various forms of royalties, taxes, and levies benefit states, including mineral resource royalties, income tax (with gold mines paying on a sliding scale), employees' income tax, dividends tax, value-added tax, social and labour plan contributions, skills development levy, and excise duties and levies, including the fuel levy (Akinseye, 2019).

The South African mineral resource royalty scheme, established in 2010, utilizes a hybrid *ad valorem* approach, with the rate dependent on the profitability ratio. This rate is then applied to the base of the total revenue from mineral sales (Cawood, 2010).

The mining companies that the study focuses on are those that exploit the narrow, tabular mineral deposits that characterize the Witwatersrand gold mines of South Africa (Figure 1).

Review of royalty costs in significant gold-producing countries

The following 10 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, 2024):

Australia
Burkina Faso
Canada
China

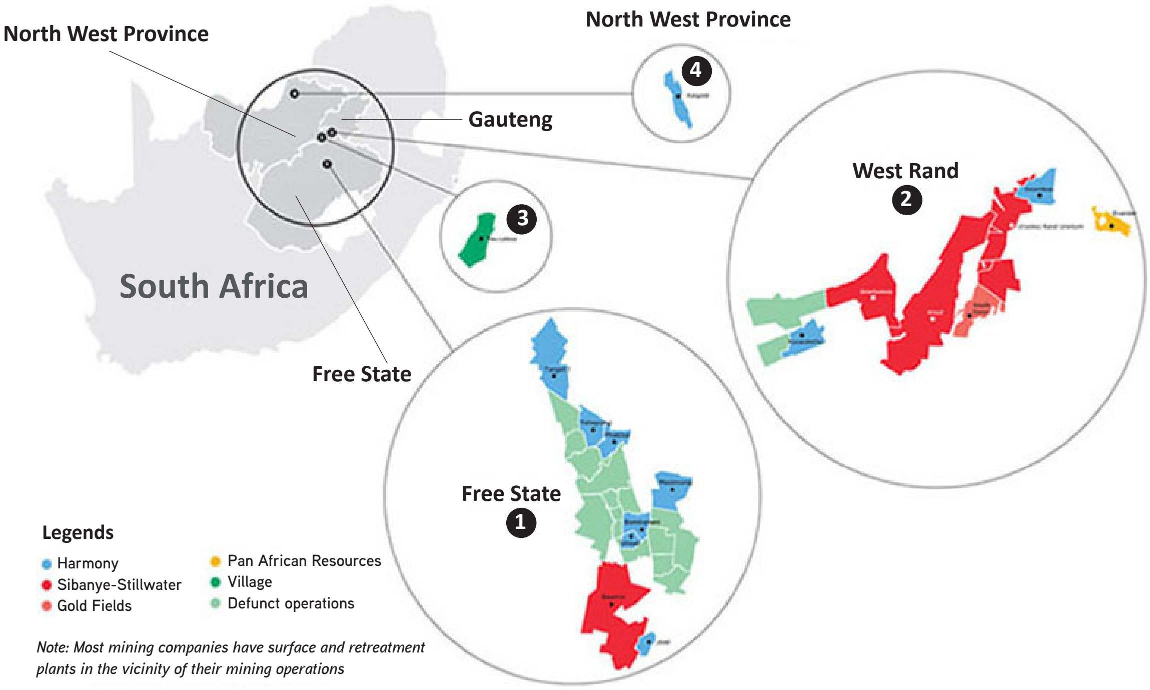

Figure 1—The Witwatersrand gold-producing areas in South Africa (Minerals Council South Africa, 2022)

Ghana
Mexico
Russia
South Africa
United States
Uzbekistan.

The predominant method used to determine the royalty is some form of *ad valorem* royalty based on the value of the mineral sold. Some countries allow some costs to be deducted when determining the amount to be paid. The accepted approach for *ad valorem* royalties is to consider them a mining cost and include the cost in the cut-off grade calculation. The South African hybrid approach. with a profit-based sliding scale applied to the total value of the mineral sales, is unique. This affects how the royalty costs should be considered for the cut-off grade determination.

South Africa has the lowest overall royalty costs of the top 10 gold-producing countries. Compared to the total cash cost (TCC), the effective rate is significantly lower than that of the other countries (estimated to be 3.8% for the mines included in the study compared to a weighted average of 7.9%). However, this favourable situation is partly due to the high overall mining costs in South Africa (US$1390 per ounce) compared to the other top 10 gold producers (average of US$952 per ounce) (S&P Global, 2024). The South African mineral resource royalty formula was developed taking marginal producers into account and yet ensuring the State received fair compensation for the resource depletion (Cawood, 2011). High-cost mines are more likely to end up as marginal mines, which makes this study important in the South African context of poverty and the need to extend the lives of the mines and avoid resource sterilization.

Problem statement

South African gold mines exploiting narrow tabular reefs face high mining costs, making many of them marginal. The associated mineral resource royalty costs significantly influence the conversion of Mineral Resources to Mineral Reserves when applying an economic cut-off grade (Lomberg and Rupprecht, 2017). Mining companies reviewed during this research project do not appear to take the profitability aspect of the mineral resource royalty formula into account when determining the cut-off grade. Understanding the profitability ratio in mineral resource royalty and income tax rates, derived from the gold formula, is essential in order to mitigate the costs associated with the mineral resource royalty when optimizing the cut-off grade.

Objective

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 in break-even grade calculation becomes the in-situ grade of the product. A block will be mined profitably if the grade is higher than the break-even grade.

Mining companies can approach the question of how to consider the mineral resource royalty costs for determining the cut-off grade in six possible ways.

➤ Ignore the implications and continue calculating the cut-off grade in the way it was done before the introduction of the tax
➤ Use the minimum rate (0.5% of total revenue)
➤ Estimate the expected rate that will be applied by looking at historical rates
➤ Estimate the expected rate by modelling the optimized 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

- ➤ Assume that the highest rate will be applied, depending on whether the mine is refining gold (rate of 5%) or selling gold production in an unrefined state (rate of 7%)
- ➤ Use a profitability optimization 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.

In an initial study published in 2016 (Birch, 2016a) it was noted that the mines reviewed considered the mineral resource royalty as a cost and included it in the determination of the cut-off grade. 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 optimization. To identify the optimal approach, a financial optimizer model has been developed which links the mineral resource block model to the financial model. This optimizer model was developed by Birch and dubbed the BirchOptimiser in his PhD thesis (Birch, 2022).

Two primary forms of taxation are considered for this study: the income tax (in the form of gold tax for gold mines) (South African Revenue Service, 2022) and the mineral resource royalty (South African Government, 2008). The gold taxes and the mineral resource royalty both have sliding scales based on the operation's profitability. In periods of higher profitability, the structure of these taxes results in a higher tax rate. The difference between the two forms of taxation is the base the rates are applied to. Income tax is paid as a percentage of the profit, while the mineral resource royalty is paid on a base allowing for a few deductions – a base close to sale revenue. These two taxes combine to ensure that the State is receiving a higher portion of the revenue at times of high commodity prices, while also providing automatic relief during difficult times.

South Africa introduced two formulae to determine the mineral resource royalty rate. Separate formulae apply to refined and unrefined mineral products. The difference between the refined and unrefined rates was introduced to encourage mineral beneficiation (Akinseye, 2019). The mineral resource royalty is considered a tax-deductible cost in determining the taxable income. This also has an impact on profitability when determining the income tax rate using the gold tax formula. When calculating the rate payable, these formulae consider the company's profitability, with highly profitable companies paying a higher rate (South African Government, 2008). Gold mines are required to refine gold to 99.5% for the refined royalty formula to apply. Rand Refinery is owned by five large South African gold mining companies (Bullionstar, 2022) and all the mines included in this study are owned by these companies. The refined royalty rate will thus be used for this study.

The refined mineral resource royalty rate is calculated as shown in Equation [1] (South African Government, 2008).

$$\text{Refined Royalty Rate } (y(r)) \quad y(r) = 0.5 + (x \div 12.5) \qquad [1]$$

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

The gold mining companies pay income tax based on the gold tax formula shown in Equation [2].

$$\text{Income tax rate (gold tax) } (y\%): \quad y(\%) = 34 - (170 \div x) \qquad [2]$$

where: x is the profit/revenue ratio multiplied by 100 to yield a whole number, and $y(\%)$ is the applicable tax rate.

The gold tax is paid on the taxable profits of the mining company and excludes non-mining income (South African Revenue Service, 2022). The tax has an element of variation due to profitability, which is considered along with the mineral resource royalty when optimizing the cut-off grade.

Tax theory describes an effective tax as one that does not disrupt economic behaviour (Otto and Cordes, 2002; Mangondo, 2006). Businesses primarily aim to generate profits, and income tax, calculated based on profits, does not alter business conduct. Therefore, income tax is considered neutral (Otto and Cordes, 2002).

In general, mineral resource royalties are not neutral unless they are purely profit-based and the royalty is treated as a tax-deductible expense. Royalties are based on total mining revenue, to which base the royalty rate is applied. They are also often treated as an expense, making them deductible for calculating taxable income. This adjustment influences the cut-off grade calculation and determines the economically viable portion of the orebody.

Break-even cut-off grade

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*'. A cut-off is generally defined as the amount of metal a ton of rock must contain in order 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 moves through various stages (Lane, 2016).

The basics of cut-off grade theory are described in Hall (2014). This is a comprehensive study of the various techniques used in the mining industry. It includes multiple value measures, including optimizing the discounted cash flow (DCF) and net present value (NPV). Lane (2016) stated that the boundary that distinguishes which material within a mineralized body is to be extracted from the remainder and treated is specified by the cut-off grade, which is, in effect, the economic definition of ore. The cut-off grade is the lowest value at which a specified ore block may be mined profitably for the planning cycle under consideration (Lane, 2016).

The cut-off grade calculation is 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 (Githiria and Musingwini, 2018).

At the break-even grade, total revenue is equal to total costs. Before 2013, gold mining companies used varied methods of reporting their mining costs. Some companies only reported mining and processing expenses and overlooked crucial factors like sustaining capital (Yapo and Camm, 2017). The World Gold Council then established a more consistent reporting method, including the all-in sustaining costs (AISC) and all-in costs (AIC) (Gianfrate, 2017). For this study, the TCC values have been used. Both the AIC and AISC values include off-mine costs and for determining the break-even grade, only on-mine costs are considered appropriate (Meredith, 2021). Equation [3] was used to determine the break-even grades that are applied as the base case for the comparisons of the various optimized approaches.

$$g/t = \frac{(\frac{TCC}{p})}{(r \times SM)} \qquad [3]$$

where g/t is the break-even grade in grams per ton, *TCC* is the all-in sustaining costs in US$ per ton, *r* is the mine recovery factor in %; *p* is the metal price in US$ per gram, and SM is the ratio of stope tons to milled tons (in %).

The reason for including the stope tons to milled tons ratio in calculating the break-even grade is that all milled tons are taken into account when stating the TCC. It is worth noting that mines do not just mill tons extracted from stopes. Other sources, such as on-reef development, vampings, and waste dilution, also contribute to total production. To determine whether stopes are profitable, the cut-off grade is applied to the in-situ face grade. Ideally, if the unit cost for stoping was available, it could be used directly. Unfortunately, this figure is not provided in companies' annual Resource and Reserve figures (Birch, 2023). The 2023 TCC figures used for this study have been obtained from S&P Global IQ (S&P Global, 2024).

In this study, the base-case cut-off grade will be determined using the basic break-even formula, which incorporates the expected mineral resource royalty cost. This base-case cut-off grade will then be contrasted with the cut-off grades derived from the BirchOptimiser, taking into account the various approaches mines can adopt regarding mineral resource royalty costs. The objective of the optimization strategy is to maximize profits. To achieve this, the BirchOptimiser will be employed to optimize the DCF and maximize the NPV using a 0% discount rate. It is worth noting that although this method can enhance NPV at higher discount rates, it has been observed to considerably reduce the mine's lifespan for a marginal NPV increase (Birch, 2016b). Further details about the BirchOptimiser can be found in Appendix A.

Mine data for the study

The study considers 2023 as the initial production year, assuming an average gold price of US$1941 per ounce in 2023 (World Gold Council, 2024). The figures for the nine gold mines used for the study are shown in Table I and have been sourced from the companies' annual Resource and Reserve reports and S&P Global IQ. The companies in this study state that the tons are run-of-mine tons delivered to the plant.

The methodology involves simulating block models based on published Mineral Resources and Reserves. Companies do not release raw block listings into the public domain so an alternative source for block listings is required. The distribution of the grades (in g/t or cmg/t) is determined using the Fit application in Palisade @Risk software and a probability function is derived (Palisade, 2014). This function is then used to populate the grade column in a blank block list. The total number of blocks in the list is selected so the total Measured and Indicated tonnage matches the published figures (using standard block sizes and the published channel and stoping widths). The resultant simulated block lists were compared to the published curves and are considered adequate for cut-off grade optimization, acknowledging potential variations in mine block sizes (Birch, 2022).

It is assumed that blocks above the cut-off grade are mineable (ore blocks), while those below are not mined. The study accepts a disparity between overall production results and published Mineral Reserves due to these assumptions. Nonetheless, the study's validity remains intact, aiming to identify an optimal approach while considering mineral resource royalty costs in cut-off grade calculations.

Results and discussion

Optimization exercise

The break-even cut-off grade for each mine was set as the base case, determined through Equation [3] using the TCC. These cut-off grades are inserted into a financial model to determine the average mining grade (AMG) and total tons above the cut-off grades. The total stope tons above cut-off grade, profit, resource utilization, and total revenue are then established using a cash flow model. This was repeated using TCC, excluding the expected mineral resource royalty costs.

This is followed by comparing the optimized cut-off grade using the BirchOptimiser where the royalty rate is set to 0%, 0.5%, the royalty cost for the previous year, and the estimated rate for the current year, and 5.0%. These cut-off grades are then inserted into the cash flow to determine the resultant stope tons above the cut-off grade and the resultant milled tons, AMG, and profit.

Finally, the BirchOptimiser is then run, allowing the mineral resource royalty rate to be variable, and the model automatically determines the optimal cut-off grade.

The following was noted for the nine mines.

- ➤ The cut-off grade determined by the break-even approach including the estimated royalty cost results in the highest cut-off grade (this is the base case).
- ➤ The cut-off grade determined by the break-even approach excluding the royalty costs is significantly lower and results in higher profit.
- ➤ 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) demonstrates the effect of the BirchOptimiser considering the lower profitability in the calculation.

Table I

Break-even grades for the mines included in the study (Sibanye-Stillwater, 2022; Harmony, 2023; S&P Global, 2024)

Mine	Stope to milled tons ratio (%)	MRF (%)	TCC (US$ per ton)	Break-even cut-off grade (g/t)
Doornkop	81.0	78.6	180	4.53
Driefontein	82.2	80.3	268	6.51
Kloof	81.2	83.0	243	5.78
Kusasalethu	84.6	82.6	301	6.90
Mponeng	68.7	79.4	324	9.52
Moab Khotsong	82.9	64.3	308	9.26
Beatrix	91.7	69.9	139	3.47
Joel	92.4	79.0	208	4.57
Tshepong (North and South)	83.8	72.5	195	5.14

- This resulted in a cut-off grade the same as or slightly lower than the break-even cut-off grade (without royalty costs).
- When the BirchOptimiser is allowed to alter the royalty rate automatically, the resultant cut-off grade is lower than when it is set to 0%. This demonstrates that the model is taking the effect of the lower profitability reducing both the mineral resource royalty and gold formula income tax rates into account and allowing more mining to take place. The overall result is higher profit.

Benefits of removing the 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 nine mines reviewed. The average break-even/cut-off grade is weighted using the total tons above the break-even/cut-off grade. The benefit of presenting the break-even cut-off grade (excluding royalty) approach is that the mines could quickly adopt this without changing their current approach for determining their cut-off grades. This results in an average reduction of the cut-off grade by 4%. However, further benefits could be derived by adopting the BirchOptimiser profit-optimized (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 results in an average cut-off reduction of 6% compared to the base case. This approach is shown to be the best when the overall profit is used as a value measure.

Stope tons above the cut-off grade

Figure 2 shows the difference in the overall tons above the cut-off grade for the three approaches.

It can be observed in Figure 2 that using the break-even grade (excluding royalties) as the cut-off grade increases the tons above the cut-off grade by 4% of the break-even grade (including royalties). An additional 2% can be mined if the profit-optimized (with variable royalty rate) approach is adopted (as determined using the BirchOptimiser).

Profit

Figure 3 shows the profit difference using the three approaches.

The difference in overall profit between the three approaches is very slight, with only an additional 0.2% being gained by adopting the profit-optimized (with variable royalty rate) approach. However, the benefits of increasing the resource utilization and extending the mines' lives need to consider a broader view of value than purely profits (Birch, 2023).

Resource utilization

An additional benefit to the higher profitability is better resource utilization. Figure 4 shows how the percentage resource utilization increases as the cut-off grade is reduced by excluding the royalty costs from the calculation and using the profit-optimized (variable royalty rate) approach.

There is a 2.0% and 3% increase in resource utilization (in kilograms) noted between the two approaches compared to the base-case approach. This is significant because it would allow more ore to be mined for the same input costs. One of the planning methods used in South African gold mines is the 'iceberg' (School of Mining Engineering, 2021). 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 utilization (considering cut-off grade and aspects like mining method and geological losses). Increasing the resource utilization by up to 3% would bring significant savings in development costs, reducing the TCC. Figure 5 demonstrates how increasing resource utilization (through a lower cut-off grade) reduces development requirements and costs and further lowers the cut-off grades.

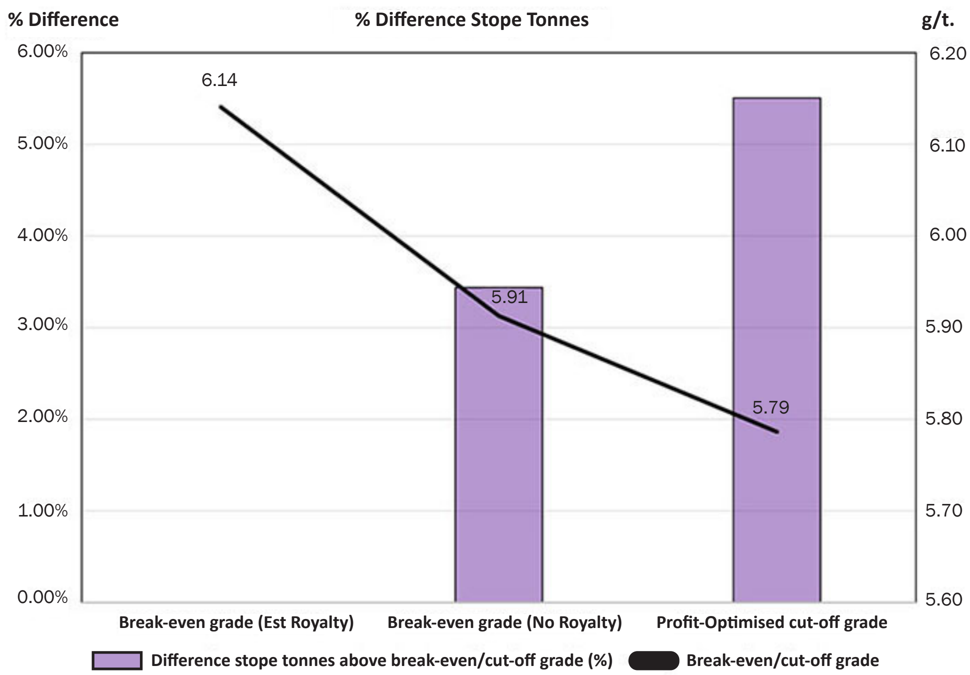

Figure 2—Percentage difference in stope tons above the break-even/cut-off grade between base-case (break-even grade including royalty costs), break-even grade excluding royalty costs, and profit-optimized cut-off grade (using variable royalty rate)

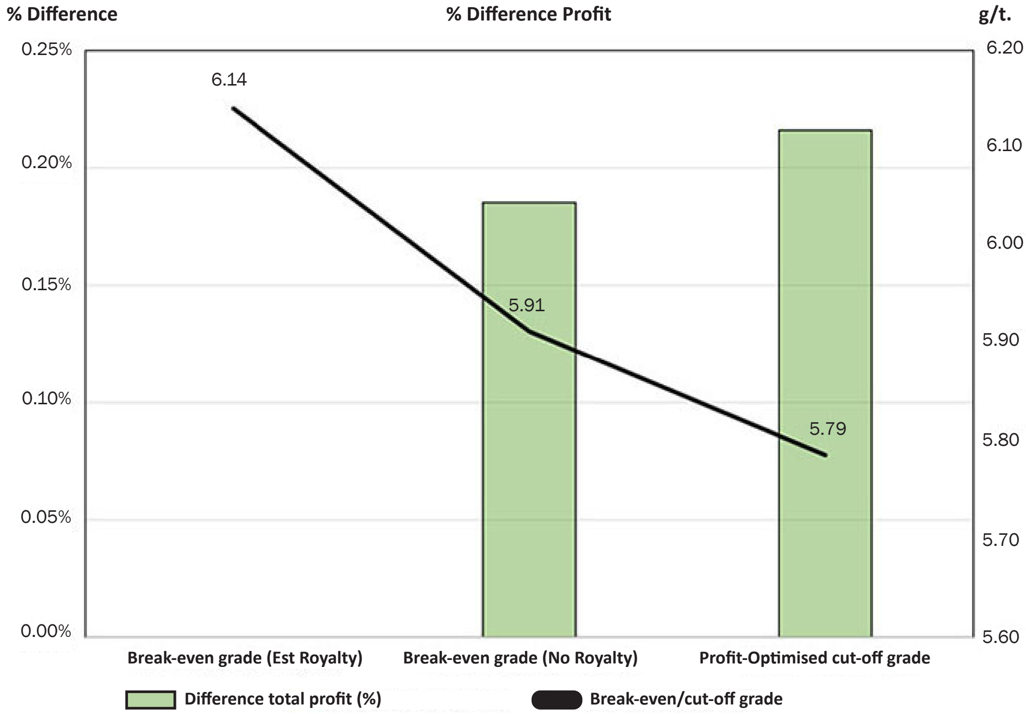

Figure 3—Percentage difference in profit between base-case (break-even grade including royalty costs), break-even grade excluding royalty costs and profit-optimized cut-off grade (using variable royalty rate)

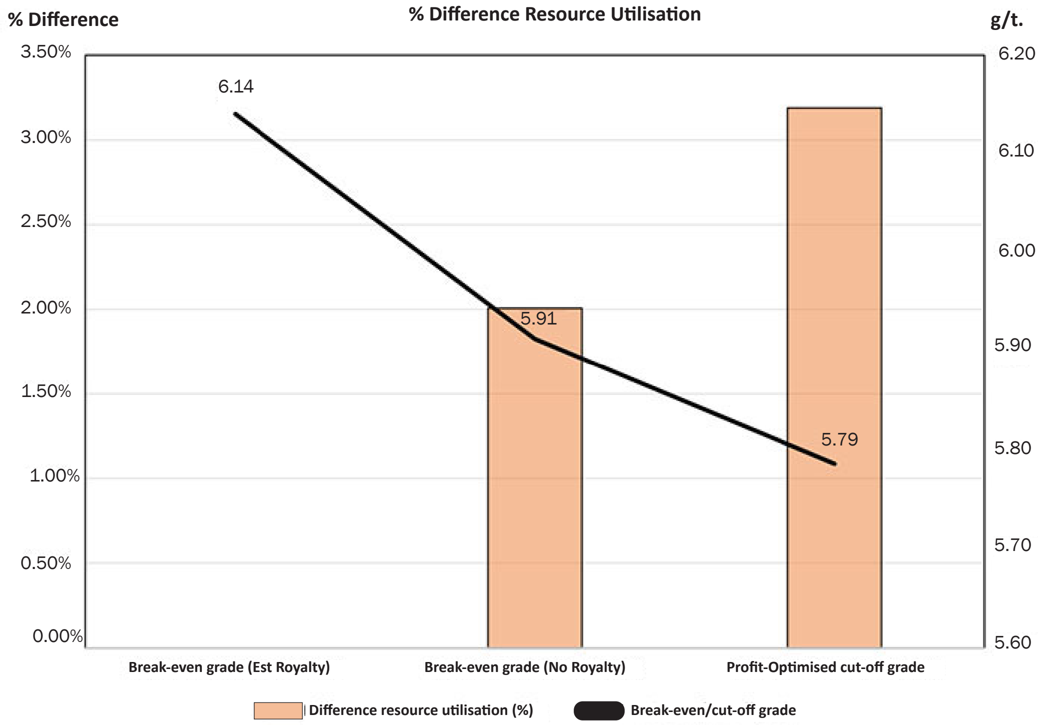

Figure 4—Percentage difference in resource utilization (kilograms) between base-case (break-even grade including royalty costs), break-even grade excluding royalty costs, and profit-optimized cut-off grade (using variable royalty rate)

Total revenue

The increase in total revenue obtained by adopting either the break-even (excluding royalty cost) or the profit-optimized (with variable royalty rate) approach is displayed in Figure 6.

Figure 6 shows that the total revenue from the mines reviewed could be increased by 2% and 3%, respectively, by adapting either the break-even (excluding royalty cost) or the profit-optimized (with variable royalty rate) approach. Although the profitability is reduced, the increased mineable reserve results in an overall increase in mining volume and profits. 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

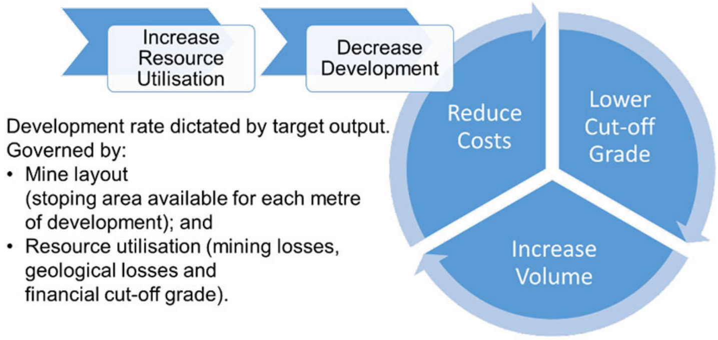

Figure 5—The spiral effect of reducing costs leads to lower cut-off grades (Birch, 2022)

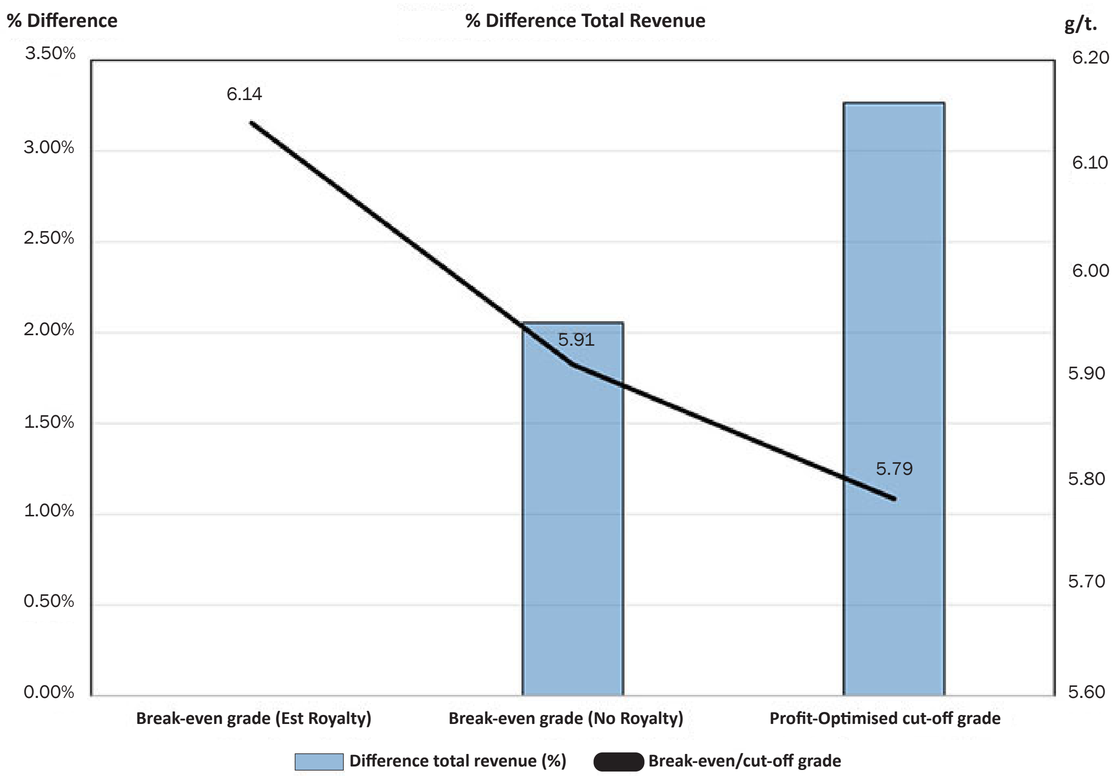

Figure 6—Percentage difference in total revenue between base-case (break-even grade including royalty costs), break-even grade excluding royalty costs, and profit-optimized cut-off grade (using variable royalty rate)

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 optimization approaches. Although they would not enjoy the benefit that a reduced profitability ratio would have on their corporate income tax rate (currently fixed at 27%) (South African Revenue Service, 2022), the benefit the reduced profitability has on the mineral resource royalty rate is expected to be the same.

Conclusions

South African gold mining companies pay income tax and royalties according to a unique formulae system. 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 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. This unique approach poses a question: *Can a decrease in mine profitability actually lower the cut-off grade and lead to an increase in profits because of the dynamics of the two formulae*?

This study has examined how the mineral resource royalty cost can be considered when determining the cut-off grade. A base case was established where the cut-off grade was determined using the break-even approach and the estimated royalty costs were included in the calculation. This was contrasted with the cut-off grade being calculated with the break-even approach – excluding the royalty costs. These results were then compared to the optimal cut-off grade determined using a financial optimizer model developed for the study (the BirchOptimiser), which uses an Excel mixed-integer linear programming Solver function. Various approaches were tested using a royalty rate set to 0%, 0.5%, the royalty cost for the previous year, the estimated rate for the current year, and 5.0%. Finally, the BirchOptimiser was allowed to determine the mineral resource royalty rate automatically.

Nine South African gold mines were included in the study. Cost and production information was obtained from the annual Mineral Resource and Reserve reports for the companies. The BirchOptimiser requires a block listing, and these were simulated from the published grade-tonnage curves. The study has shown that total stope tons above cut-off grade, profit, resource utilization, and total revenue can be improved by excluding the royalty cost from the break-even cut-off grade calculation. This results in an average reduction in the cut-off grade by 4%. The BirchOptimiser has identified that additional profit gains can be realized by reducing the cut-off grade further. The average cut-off reduction from the base case, following this approach, is 6%. The reduced profitability results in lower royalty and income tax rates.

While the actual differences in profits obtained from the study are minor (0.2% compared to the break-even base case), significant gains in stope tons above cut-off grade and resource tonnage utilization (6%), and total revenue (4%) can be achieved. The higher resourceutilization (3%) would more than offset the development needed to maintain the mine's target gold output, leading to lower TCC. This, in turn, will allow further reductions in the cut-off grade, and increase profits and the life of mine.

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References

Akinseye, P.O. 2019. Modifying the South African mining royalty regime for optimal mineral resource use and management of mineral rents. PhD thesis, University of the Witwatersrand.

Birch, C. 2016a. 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*, vol. 116, no. 3. https://doi.org/10.17159/2411-9717/2016/v116n3a4

Birch, C. 2016b. Impact of discount rates on cut-off grades for narrow tabular gold deposits. *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 116, no. 2. https://doi.org/10.17159/2411-9717/2016/v116n2a2

Birch, C. 2022. Understanding the impact of the South African mineral resource royalty regime on tabular gold deposits: an approach for cut-off grade optimisation. PhD thesis, University of the Witwatersrand.

Birch, C. 2023. Multiple-criteria cut-off grade optimisation utilising Excel Solver. *Proceedings of APCOM 2023. Intelligent Mining: Innovation, Vision, and Valu*, Rapid City, South Dakota. Society for Mining, Metallurgy & Exploration (SME), Littleton, CO.

Bullionstar. 2022. Rand Refinery. https://www.bullionstar.com/gold-university/rand-refinery

Cawood, F. 2010. The South African Mineral and Petroleum Resources Royalty Act – Background and fundamental principles. *Resources Policy*, vol. 35, no. 3, pp. 199–209. https://doi.org/10.1016/j.resourpol.2010.03.003

Cawood, F. 2011. An investigation of the potential impact of the new South African Mineral and Petroleum Resources Royalty Act. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 111, no. 7. https://www.saimm.co.za/Journal/v111n07p443.pdf

Gholamnejad, J. 2008. Determination of the optimum cutoff grade considering environmental cost. *Journal of International Environmental Application & Science*, vol. 3, no. 3. pp.186–194.

Gianfrate, G. 2017. All that glitters: Gold mining companies' market reaction at the issuance of the "All-in Sustaining Costs" guidance. *Journal of Accounting and Public Policy*, vol. 36, no. 6, pp. 468–476. https://doi.org/10.1016/J.JACCPUBPOL.2017.09.004

Githiria, J. and Musingwini, C. 2018. Comparison of cut-off grade models in mine planning for improved value creation based on NPV. *Proceedings of the Society of Mining Professors 6th Regional Conference*. Southern African Institute of Mining and Metallurgy, Johannesburg. pp. 347–362.

Hall, B. 2014. Cut-off Grades and Optimising the Strategic Mine Plan. Australasian Institute of Mining and Metallurgy, Melbourne.

Harmony. 2023. Mineral Resources and Mineral Reserves report. 162 pp. https://www.harmony.co.za/business/resources-reserves

Lane, K. 2016. The Economic Definition of Ore. Comet Strategy, Brisbane, Australia.

Lilford, E.V. 2017. Quantitative impacts of royalties on mineral projects. *Resources Policy*, vol. 53, pp.369–377. https://doi.org/10.1016/j.resourpol.2017.08.002

Lomberg, K. and Rupprecht, S.M. 2017. The 2016 SAMREC Code. *Journal of the Southern African Institute of Mining and Metallurg*, vol. 117, pp. 1095–1100. https://doi.org/10.17159/2411-9717/2017/v117n12a1

Mangondo, K. 2006. The economics of gold mining taxation. M.Com dissertation University of South Africa. https://uir.unisa.ac.za/bitstream/handle/10500/2265/dissertation.pdf

Meredith, E.D. 2021. The effect on net present value of cut-off grades applied to various reef types using different mining methods. MSc dissertation, University of the Witwatersrand.

Microsoft. 2022. Define and solve a problem by using Solver. https://support.microsoft.com/en-us/office/define-and-solve-a-problem-by-using-solver-5d1a388f-079d-43ac-a7eb-f63e45925040 [accessed 22 January 2022].

Minerals Council South Africa. 2022. Gold. https://www.mineralscouncil.org.za/sa-mining/gold [aAccessed 1 December 2022].

Otto, J. and Cordes, J. 2002. The regulation of mineral enterprises: A global perspective on economics, law and policy. Rocky Mountain Mineral Law Foundation, Westminster, CO.

Palisade. 2014. Monte Carlo simulation. https://www.palisade.com/risk/monte_carlo_simulation.asp

Rendu, J. 2008. An introduction to cut-off grade estimation. Society for Mining, Metallurgy & Exploration (SME), Littleton, CO.

Sibanye-Stillwater. 2021. Mineral Resources and Mineral Reserves report. 189 pp. https://www.sibanyestillwater.com/news-investors/reports/annual/2021/

S&P Global. 2024. S&P Capital IQ Pro. S&P Global Market Intelligence. https://www.:spglobal.com/marketintelligence

School of Mining Engineering. 2021. MINN7050A Mineral Resource Management course notes. University of the Witwatersrand, Johannesburg.

South African Government. 2008. Mineral and Petroleum Resources Royalty Act 28 of 2008. *Government Gazette*, no. 521. Pretoria. 13 pp.

South African Revenue Service. 2022. Guide for tax rates/duties/levies. Pretoria. 119 pp.

Taylor, H.K. 1972. General background theory of cut-off grades. *Transactions of the Institute of Mining and Metallurgy*, vol. 96(A). pp. 204–216.

World Gold Council. 2024. Gold Demand Trends Full Year 2023. https://www.gold.org/goldhub/research/gold-demand-trends/gold-demand-trends-full-year-2023 [accessed 10 May 2024].

Yapo, A.G. and Camm, T.W. 2017. All-in sustaining cost analysis: Pros and cons. *Proceedings of the SME Annual Meeting*, Denver, CO. https://digitalcommons.mtech.edu/cgi/viewcontent.cgi?article=1007&context=mine_engr

Appendix A. The BirchOptimiser

The BirchOptimiser performs two functions. The first 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 is a financial optimizer that uses the Excel Solver function to optimize the cut-off grades. The optimized 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 layout for the BirchOptimiser used for this study is presented in a series of tables spread across two Excel sheets (the Blocklist and Cashflow sheets). The various tables are depicted in Figure A-1.

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 Resources and Reserves into the public domain.

The cash flow used in this study is relatively simple and based on the one used for the Mine Financial Valuation courses presented at the University of the Witwatersrand School of Mining Engineering. 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.

The production rate for this study uses the anticipated annual milled tons for the mine as published in the annual reports. The companies also publish the stoping width (SW) and milled width (MW), and this ratio is used to determine how much of the total annual tonnage is expected to be derived from stope faces.

The stope-face tons available to mine above the cut-off grade are determined from the block listing using an Excel = SUMIF function. If the estimated grade of a block is above the cut-off grade, it is included in the available tonnage. The AMG is determined by calculating the total metal in the s above the cut-off grade divided by the total tonnage of those blocks.

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 tons exceed the projected annual tonnage, the total annual tonnage will be mined, or only the remaining tonnage will be mined. Once the tons are depleted, no more mining takes place. The model only includes the Measured and Indicated resource blocks.

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

The MRF is determined by the mine call factor multiplied by the plant recovery factor. This is applied to the metal mined to determine how much is available to be sold and generate revenue.

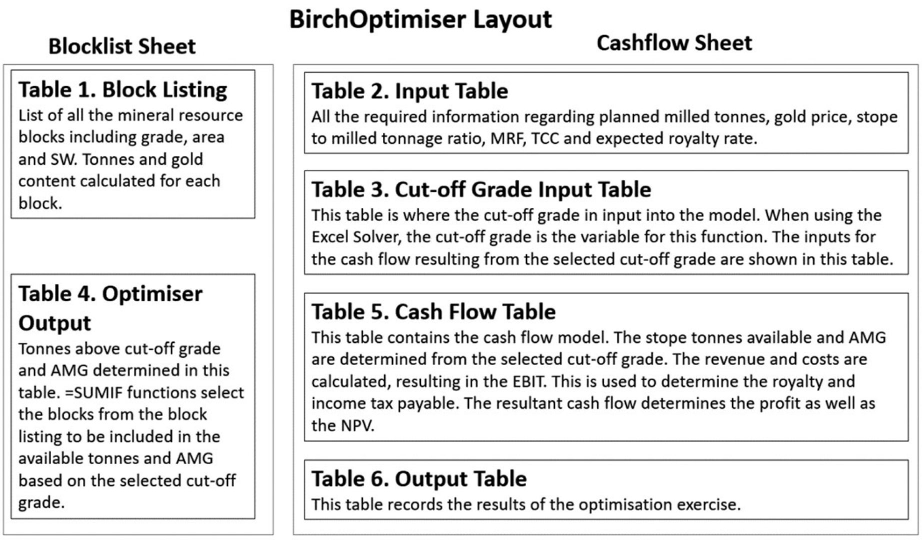

Figure A-1—The layout of the BirchOptimiser (Birch, 2022)

Revenue

This study states the metal price and resultant revenue in US dollars or South African rand. Due to the volatility of the South African rand and uncertainty of the exchange rates, the US dollar has been used.

The 2023 gold price is used for this study. The cash flows are in real (constant) monetary terms and use 2023 costs, so the gold price used is for the same period.

The formula to determine the gross sales revenue is shown in Equation [A-1].

Gross sales revenue (GSR):

$$GSR = (Au(oz) * p) \quad \text{[A-1]}$$

where Au(oz) is the metal recovered in troy ounces, and p is the metal price in US dollars per ounce.

Costs

The TCC figure has been used for this study 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 dollars per ounce operating expense (OpEx) cannot be used for the model. US dollars per ton OpEx is a more meaningful measure of the mines' production efficiency for this study and is thus used. 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 is 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 dollar per ton OpEx.

Earnings before interest and tax

The EBIT is simply the gross sales revenue minus the total costs, as shown in Equation [A-2].

EBIT (US$):

$$EBIT = (GSR - TC) \quad \text{[A-2]}$$

where GSR is the gross sales revenue, and TC is the total costs in US dollars.

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.

For the gold mines, the refined royalty formula is applied to the gross sales revenue. The gold tax formula determines the income tax rate and is applied to the taxable income. Both of these formulae use the profitability of the mine to determine the rates. The mineral resource royalty is a tax-deductible cost that affects the taxable income amount as well as the profitability used in the gold tax formula. 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):

$$CF = (EBIT - MRR - it) \quad \text{[A-3]}$$

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

Excel Solver

The financial optimizer model created for this study uses the Excel Solver optimization tool to determine the cut-off grade. The Excel Solver is bundled with Excel, a widely used optimization 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) (Microsoft, 2022).

It is important to note that Solver has a few limitations. Firstly, the standard Microsoft Excel Solver is limited to 200 decision variables for both linear and nonlinear problems. Secondly, the limit on constraints depends on the type of model (linear or nonlinear) and the form of the constraints (Frontline Systems, 2023). Finally, it is worth mentioning that both the target cell and the decision variable cell must be on the same sheet for Solver to function properly.

Solver has three algorithms that it uses:

- 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 inconsistent 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 MCF and ratio between stope tonnage and total milled tonnage are also required. 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 maximize the profit. ◆