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Review of cut-off grade optimisation from Southern African mines. Student assignment based observations

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ABSTRACT

Mines classify their resource as ore or waste in various manners. A common approach is to apply a cut-off grade. How this cut-off grade is optimised, has been extensively researched and there are thousands of academic papers covering this topic in the public domain. The question for this paper is if mines are actually considering these various techniques in practice. The background to this research paper is the MSc (Mineral Resource Management) at University of Witwatersrand student assignments where this has been a topic for 2014, 2015, 2016 and 2017. The focus of the students' research is: "Is it ore or is it waste?". This question was posed to the students to research it on their operations where they are employed.

45 Student assignments representing 39 individual mines were reviewed. These include gold, platinum, coal, diamond, iron ore, manganese, copper and zinc mines. These mines are in South Africa, Namibia, Botswana, Zimbabwe, Lesotho and the Democratic Republic of the Congo.

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 basic break-even grade and Lane's algorithm and do not optimise the cut-off considering other factors like volume or net present value. There is some evidence of optimisation considering the volume/cost relationship to identify the 'hill of value'. The Whittle Optimiser as well as the Lerchs-Grossman algorithm is applied for some of the open pit mines reviewed and the optimisation is focused on the NPV. Few, if any of the latest optimisation approaches, are found applied on the mines at operational level reviewed by this exercise.

1. Introduction

Mining companies calculate a cut-off grade to determine what portion of the mineral deposit can be mined economically. Many companies apply the break-even grade as the cut-off grade. The break-even grade takes into account the price of the commodity, the expected mine recovery factor, the unit cost to mine the ore, as well as the fixed costs for the mine. By using the planned extraction rate, expected recovery factor and production costs, the variable to break-even then becomes the in-situ grade of the material being sold. As long as the grade is higher than the break-even grade in a particular mining block, the block will be mined profitably. The estimation of the grades for each mining block is determined from sampling the mineral deposit and projecting the values into the area to be evaluated. Various techniques are used to do this - including nearest neighbour, inverse distance squared and kriging. To determine if a mining block is classified as ore or waste, the estimated value is used for this classification.

The most common cut-off grade optimisation techniques consider the break-even grade and then adapt this to volume ('hill of value' (Hall, 2014)), stage of the mine's life (Lane, 1988) or net present value (NPV) like the Whittle Optimiser (Whittle, 2015).

The two week long Mineral Resource Management Module forms part of a 50/50 MSc degree in Mining Engineering at the University of the Witwatersrand. This course is intended to enable the student to understand the role of a Mineral Resource Manager and develop a Mineral Resource Management system on their own operations. On concluding the module, the student should have a better understanding of how Mineral Resource Management is developing into Mineral Asset Management. This is due to the changing environment of the mining industry. The student will then be better positioned to link all the elements of the mining value chain with the focus on the overall return on invested capital rather than traditional measures of value.

The background to this research paper is the student assignments identifying how mines evaluate their mineral resource and classify it into ore or waste and has been a topic for 2014, 2015, 2016 and 2017 classes. The question posed to the students to research on the operations where they are employed, is as follows:

"Discuss how the delineation of ore and waste is determined on YOUR

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operation, or an operation you are familiar with. What are the parameters used for this and how are these determined? Is this optimised and how does this optimisation occur? In your opinion, is this method effective and how could it be improved."

The wording for the 2016 and 2017 classes individual assignment was altered to include consideration of the Theory of Constraints (TOC) and if optimisation occurs with the view to improve flow of ore through the system. This aspect has however not been considered for inclusion in this review which is focused on delineation or ore and waste, particularly the application of cut-off grade optimisation. The assignments have been reviewed to identify current trends and effectiveness of cut-off grade optimisation on various Southern African mining operation. The author has used this approach to research previously. The advantage of using student assignments for gathering information is that numerous countries and commodities can be compared quickly and with no real costs to the university (Birch, 2017).

A total of 45 assignments were analysed representing students from 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.

2. Cut-off grade optimisation

2.1. Commonly applied methods

For decades the idea of optimising the cut-off grade to maximise financial return has been researched. The advent of computers allowed far more refined models to be established cutting the time and man-hours associated with manual calculations. The resource could be divided into smaller blocks representing the smallest mining unit (SMU). Halls et.al approached the question of determining the optimal ore reserves and plant size by conducting incremental financial analysis in 1969 (Halls et al., 1969).

Lane, in his book "The Economic Definition of Ore", 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 (Lane, 1988). The algorithm considers three main constraints, which are mining, concentrating and refining. Economic factors (selling price and unit costs) and technical factors (the grade distribution and the various capacities of the mine) are included in the algorithm with the aim of maximising either the profit or NPV. The NPV is usually considered the dominant economic criterion because it takes into consideration the time value of money (TVM) (Lane, 1988).

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 various measures of value including optimising the discounted cash flow (DCF) and NPV (Hall, 2014).

The operational cut-off grade calculation is essentially very simple. It determines the grade required for a unit of ore 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. From these the total unit cost can be obtained (typically expressed in Rands/tonne). Other factors required for the cut-off grade calculation is the mine recovery factor (MRF) - which is the mine call factor (MCF), multiplied by the plant call factor (PCF). The commodity price in Rands/gram is obtained by the commodity price in US$ (usually quoted in troy ounce for gold and platinum) and the exchange rate. These are all estimates and subject to variation throughout the period which the cut-off grade is to be used - and thus add to the financial risk to the investors if they change significantly. This can be expressed as follows:

$$\text{Unit Total Cost(\$/tonne)} = \left(\frac{\text{Total Fixed Cost(R/tonne)}}{\text{Volume(tonnes)}}\right) + \text{Unit Variable Cost(\$/tonne}$$

$$\text{i.e. UTC} = \left(\frac{\text{TFC}}{\text{X}}\right) + \text{UVC}$$

$$\text{Unit Revenue (\$/g)} = \text{Grade (g/tonne)*Mine Recovery Factor (\%)} \text{*Price (\$/gram)}$$

$$\text{i.e. UR} = \text{Grade*MRF*Price}$$

Thus

$$\text{Grade*MRF*Price} = \left(\frac{\text{TFC}}{\text{X}}\right) + \text{UVC (since unit revenue} = \text{unit total cost)}$$

$$\text{Grade} = \frac{((\frac{\text{TFC}}{X}) + \text{UVC})}{(\text{Price*MRF})}$$

A more advanced method for determining the cut-off grade is to use the block listing for each individual ore body. The block list contains gold grades in grams/ tonne (g/t) or centimetre grams/tonne (cmgt), the channel width, stoping width and area of the blocks. From the area, stoping width and specific gravity, the tonnes can be determined for each individual block. The ratio of tonnage from stope faces compared to all the tonnage milled, is determined from a simple ore flow. This ore flow considers face tonnage, gully dilution and other sources of dilution, historic discrepancies and how much development waste will be hoisted and milled with the ore. The ore flow also uses the historic MCF and PRF to calculate the planned MRF for use 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 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, 2016). Fig. 1 shows the relationship between the tonnage from the ore resource blocks, the cut-off grade and the average grade of the blocks above the cut-off grade. The average mining grade is then determined and this is then the grade which the overall reserve is mined at.

The costs that are included in the cut-off grade calculation are subject to much debate and often change through the life of the project. Whilst a company is still recovering the initial capital costs, a budget cut-off grade can be used. This will include the costs, as well as an additional percentage to recover the initial capital costs quickly. In the final stages of the mine, development costs are minimal and certain areas can be mined that were previously considered below cut-off grade (Border, 1991). This is called a marginal cut-off grade (Lane, 1988).

Minnitt looked at how Lane's cut-off grade calculations were being adapted to Wits-type gold mines in 2004 (Minnitt, 2004) and found that the application of the net present value (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. Both Lane and Minnitt consider the NPV calculated over the life-of-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. These results in shorter life-of-mine and less extraction of the mineral resource (Birch, 2016). The discount rate used for the calculation of the DCF and resultant NPV are critical to the cut-off grade calculation. This discount rate is essentially the cost-of-capital and it is usually calculated by the weighted average cost of capital (WACC). This considers all the sources of capital required for a project (equity and debt), the portion of the total each source makes and its