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Mining rate optimization considering the stockpiling: A theoretical economics and real option model

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ABSTRACT

In the extraction of metal from a mine, the intermediate ore between the economic and the breakeven cutoff grade is usually stockpiled for future processing once the mine is depleted. This research establishes a theoretical two-stage economic model to derive the value of this stockpile and how it affects optimal mining rate. By deriving the optimal condition for objective profit function and parameterized analysis, this research finds the stockpiling option can significantly boost a mine's profit. Processing the stockpiled material affects the optimal mining rate and cutoff grade strategy significantly compared to the case that it is not processed. The research also investigates the optimal mining rate's sensitivity to input variables such as commodity price, discounting rate, capital cost, and processing capacity, etc. In addition, the intrinsic advantages of this approach compared to the broadly used Lane's model (1988) are discussed.

1. Introduction

In the extraction of metal from a mine, the intermediate ore between the economic and the breakeven cutoff grade is usually stockpiled for future processing once the mine is depleted. As widely studied and discussed, the economic cutoff grade is defined as the cutoff grade strategy that maximizes the net present value of a mine by considering the opportunity cost, which is usually higher than the breakeven cutoff (Zhang et al., 2015). This research establishes a two-stage mining model to derive the value of stockpiling and how it affects mining decisions, i.e. the optimal mining rate. For decades, industry practitioners and academic researchers have been interested in questions on stockpiling, such as that how valuable the stockpiled material is and its impact on the optimal mining strategy (Young, 1991); when is the best time (or price threshold) to process the stockpiled material (Dixit and Pindyck, 1994; Conrad, 2000; Zhang et al., 2015); how price expectations will impact ore's quality selection (Withagen, 1998; Lee et al., 2006); and how will the stockpiled ore's quality changes as it is processed (Mason, 2011). Nevertheless, there is only limited theoretic work studying the stockpiled option and its impacts on mining production rate.

Based on a theoretical two-stage model, this research examines the production of stockpiled material after depletion. The profit functions in both stages and their first order conditions (FOC) are formulated explicitly and the optimal mining rate is obtained. Profit from the stockpiled material in our model accounts for more than 15% of the mine's total value. The model also examines optimal mining rate's sensitivity to input variables, such as the commodity price, the capital cost and the processing capacity.

This paper is organized as following: Section 2 reviews the previous relevant literature. Section 3 describes the two-stage model considering the stockpiling of the intermediate grade material, and derives the profit-maximizing conditions. Section 3 also analyzes the two-stage production model, the profit function, as well as the first order condition of the objective function. Section 4 discusses the results and compares it with the two-stage model with Lane's (1988) model. Conclusions are provided in Section 5.

2. Literature review

Lane's (1988) model has been adopted in the mining industry for decades to determine the optimal cutoff grade strategy for metal mines. By maximizing the net present value of a mine, the Lane model suggests a series of economic cutoff grades that are usually higher than the minimum grade that is economic to be processed, i.e. the breakeven or heuristic cutoff. As shown in Fig. 1,

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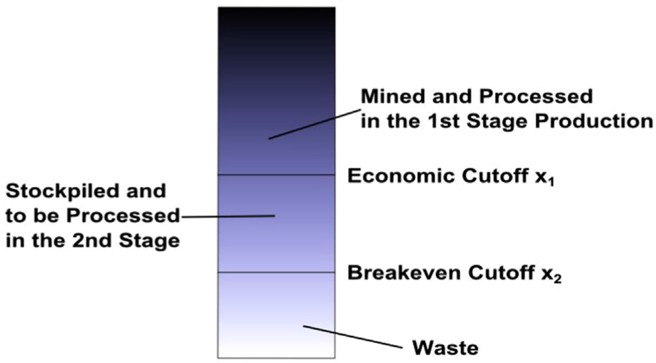

Fig. 1. A two-stage production model with cutoff grades and processing the stockpile material.

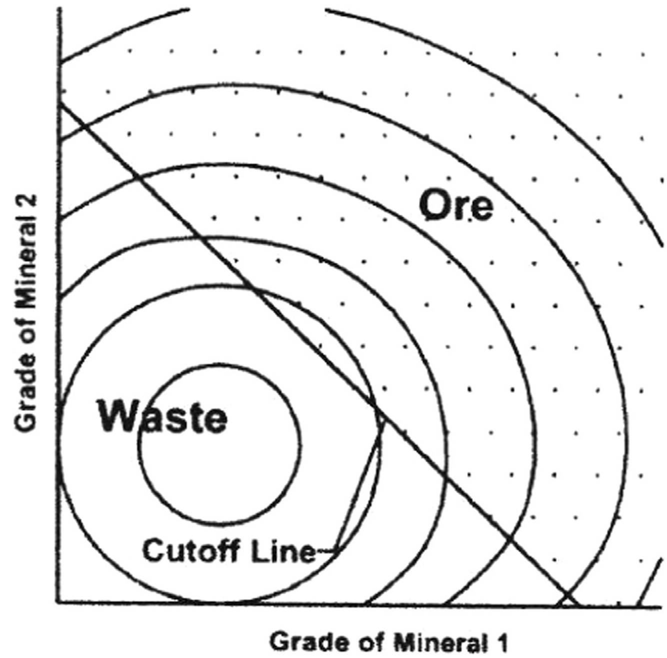

Fig. 2. Two dimensional grade and tonnage distribution of deposit (Asad, 2005).

the portion of the materials with the highest quality (the part with dark color in Fig. 1) is mined and processed early in production. This strategy leaves a portion of ore not processed, which may still generate positive cash flows. These intermediate grade materials (the middle part in Fig. 1) are extracted during the production time, and usually stockpiled beside the mine to be processed after the mine is depleted. Although mined during the production, the lowest grade portion of the deposit (the part with light color in Fig. 1) is regarded as waste and never processed.

Theoretical work by Krautkraemer (1988) uses a cylinder model and optimal control approach to explore the optimal strategy of mining rate and how changes in mining cost and metal price impact the strategy. It is found that, if the price increases more quickly than the discount rate, the mine is depleted sooner with a higher cutoff grade. Krautkraemer (1989) extends the cylinder model to study the impacts of variability in price on the selection of ore's quality in the metal deposit. However, the stockpiling question was not examined in this model.

Epaulard and Pommeret (2003) derive a closed-form solution of optimal extraction strategy for non-renewable resource based on a recursive utility approach. Both uncertainties in resource stock and technical progress are considered. It is found that uncertainty in metal price leads to a conservative use or stockpile of the resource for future extraction. Cairns and Shinkuma (2003) examine the relationship between commodity price and the choice of cutoff grade, which also arises in the two-stage model proposed in this research. A follow-up similar work by Cairns and Davis (2007) addresses the optimal stopping rule for nonrenewable resource extraction against the resource's quality and expectations on price, and extend the model to sequential development and timing issues of natural resource projects.

Asad (2005) models two minerals' grades and tonnage as a series of two-dimension contours. Each axis in diagram (as shown in Fig. 2) represents the grade for one mineral. A straight line is drawn on the area of contours, and the intercept of the line with one axis represents the cutoff for one mineral in absence of the other. Solving for the optimal cutoff policy for the two minerals is equivalent to determining the pair of cutoff intercepts maximizing the net present value of the mine. Asad solves for the economic cutoff grade, and considers processing the intermediate grade material after exhausting the mine by a numerical iterative method. It is found that stockpiles, with the advantage of no additional mining cost, can generate a significant amount of additional positive cash flows. Asad's work can be improved by exploring the impacts of the stockpiled on the mining strategy, i.e. the optimal mining rate. In this research, it is assumed that the stockpiling is stocked just on ground besides the processing facility with no degrading, additional capital expenditure; the unit cost of material re-handling is assumed to be the same as processing the ores from the mine.

There are also several pieces of literature that have explored the issues of ore quality, cutoff grade, and breakeven grade in a metal mine using numerical methods. Dimitrakopoulos et al. (2007) use stochastically simulated reserve models for designing open pit mines, and apply the approach in a gold deposit. It is found that both uncertainties from ore quality and gold price will lead to a reduction in mining production. Osanloo et al. (2008) address the environmental concerns when determining the optimal cutoff grade based on copper deposits, which can minimize the adverse environmental impacts of the mining projects. They find that an appropriate chosen cutoff strategy can help to mitigate the adverse environmental impacts of mining activities and treating the waste. Shafiee and Topal (2010) argue that the stockpiled mineral products such as gold can mitigate the negative impacts of uncertainty in market, and provide the mining companies an option for hedging strategy. Nieto and Zhang (2013) study the cutoff grade for a by-product mine based on a rare earth case of Dysprosium and Neodymium. It is found that the changes in the by-product's price can lead to a significant shift in the primary product's cutoff. Franco-Sepúlveda and Velilla-Avilez (2014) review the relevant work on a mine's cutoff grade using a hypothetical gold mine to illustrate Lane's algorithm that leaves the intermediate grade material stockpiled. However, there is a gap in literature addressing the interaction of stockpiled material and the grade selection in mining operations.

3. A two-stage production model

3.1. The general model

In this section, a model of two-stage production of a metal deposit with variety in quality is presented. There are two stages of production (as shown in Fig. 1): the first stage production includes mining the material in deposit with a constant production rate of M, processing the part of the mined material with quality higher than cutoff x_1 in the time before the depletion; the part of mined material with quality lower than x_1 (the intermediate grade material) is stockpiled for the second stage production after the