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An uncertainty based multi-criteria ranking system for open pit mining cut-off grade strategy selection

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ABSTRACT

Cut-off grade strategy (COGS) is a concept that directly influences the financial, technical, economical, and environmental issues in relation to the exploitation of a mineral resource. Despite the simple definition of cut-off grade, the COGS problem is one of the complex and complicated problems in the mine planning process. From the optimization point of view, the COGS with an objective of maximizing the present value of future cash flows is a non-linear and a non-convex problem that even in its deterministic form can be solved using approximate optimization methods. This optimization problem will also be more complex and complicated under uncertainty conditions. This paper proposes an uncertainty based multi-criteria ranking system to investigate the problem of COGS selection considering metal price and geological uncertainties. The proposed system aims at selection of the best COGS among technically feasible alternative COGSs under uncertainty circumstances. Our developed system is based on integrating metal price and geological uncertainties as well as operating flexibility to close the mine early. We incorporate this operating flexibility into the proposed system using a Monte Carlo based real options (RO) valuation model. For this purpose, in addition to the expected value, other risk criteria are considered to rank the alternatives. These risk criteria include abilities of strategies in producing extra profits, minimizing losses, and achieving the predefined goals of the production. In this study, the technically possible COGSs are generated using the Lane comprehensive algorithm. To demonstrate the effectiveness of the proposed system, we utilize data of an Iranian gold mine. Results show that the proposed system outperforms conventional methods in the sense that it shows significantly lower average mis-ranking than the other methods and also selects a strategy with a higher value. The sensitivity analysis of the proposed system relative to the gold price shows that the system is highly dependent on the parameters of the stochastic process used to model the evolution of the metal price. Therefore, special consideration should be given in estimating stochastic process parameters.

Introduction

Taylor (1972) defines the cut-off grade as an operating control that could be used to choose one of the two possible actions that are going to take place on a specified amount of rock. In other words, it determines the routing of the specific materials inside a reserve. Conventionally, in open pit mine planning and design, two types of cut-off grades are defined: (1) the break-even mine cut-off grade, which is used to determine if a block of material deserves to be mined or not while trying to determine the ultimate pit limits; (2) the milling cut-off grade, which determines how the mined block should be treated, such as sending for further processing or taking to the waste dump (Dagdelen, 1992). The milling cut-off grade, which is also known as the cut-off grade strategy (COGS) or exploitation strategy has a determinant role on the optimality of the mining operation. The most comprehensive model of COGS optimization was developed by Lane (1988). His model reveals that optimum COGS depends not only on the economic parameters but also on all the salient technological features of the mining operation and ore-body (Cairns and Shinkuma, 2003).

The goal of an open pit mine planning is to find an optimum plan resulting in the highest Net Present Value (NPV) while meeting several technical and operational constraints. Hence, once the geologic block model is built, a mine planner performs the planning by answering the three following questions (Dagdelen, 2007): (1) Should a given block in the model be mined or not?; (2) If it is to be mined, when should it be done?; (3) Once it is mined, how should it be processed (OR: where should it be sent?)?

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Describing the solution of the above-mentioned questions, as discussed thoroughly in the literature (Dagdelen, 2007; Osanloo et al., 2008), is out of the scope of this paper. However, the solution for the third question carries the same solution for the COGS optimization problem. Conventionally, planning is done in a circular manner as shown in Fig. 1. Hence, any wrong COGS will certainly lead to wrong planning, inefficient performance of different stages of the mining operation, and considerable losses.

Traditionally, a constant price trend and a grade tonnage curve estimated from the kriged grades are used in open pit mine planning. But the real situation is much more complex, where mining investments are often associated with diverse sources of both endogenous and exogenous uncertainties. Recently, much research has tried to address the issue of geological and market related uncertainties in the mining industry where their adverse effects could cause substantial losses of millions of dollars (Osanloo et al., 2008).

In this respect, some outstanding work has been done incorporating geological uncertainty in long term mine planning using simulation based optimization and stochastic programming methods (Dimitrakopoulos and Abdel Sabour, 2007; Gholamnejad and Osanloo, 2007; Osanloo et al., 2008). While market related uncertainties in mining investments are resolved employing the modern stochastic valuation method, known as Real Option (RO) valuation. The RO valuation is an alternative approach to the conventional Discounted Cash Flow (DCF) model. Brennan and Schwartz (1985) applied the RO analysis in the mineral industry for the first time, and since then it has been extended by researchers considering various types of flexibilities and employing different analytical and numerical methods. Researchers have confirmed that the RO valuation performs better than the DCF approach under uncertainty conditions. It also provides a basis for developing flexible mine plans by valuing the strategic and managerial flexibilities in response to uncertain market conditions (Mardones, 1993; Trigeorgis, 1996; Frimpong and Whiting, 1997; Samis and Poulin, 1998; Abdel Sabour and Poulin, 2006; Samis et al., 2006; Dimitrakopoulos and Abdel Sabour, 2007; Cortazar et al., 2008; Akbari et al., 2009).

Despite the usefulness of these methods, they suffer from some important shortcomings. These shortcomings include making subjective judgments in the decision making process, considering constant market conditions, and the weakness of the conventional DCF approach in valuing managerial flexibilities inherent in the mineral industry. Although the RO valuation is able to value managerial and operating flexibilities, like conventional methods, it does not necessarily prescribe the best alternative among the available alternatives and the results are often interpreted subjectively.

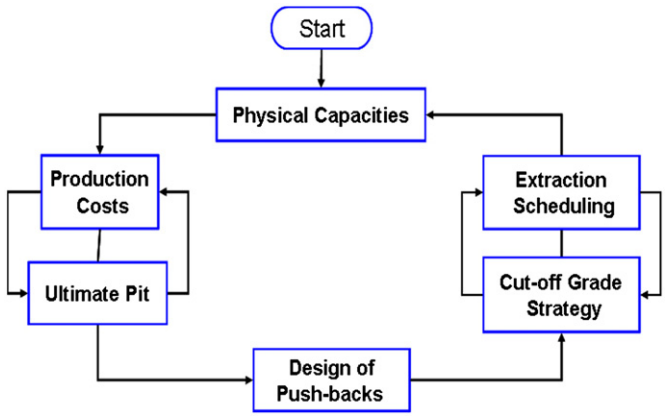

Fig. 1. Steps of traditional planning by circular analysis (Dagdelen, 2007).

Recently, according to the new developments in the simulation based RO valuation, researchers have attempted to develop multi-criteria ranking systems with the aims of minimum subjective judgments, sound quantification of uncertainties and valuation of management flexibilities for appraisal of investments in minerals industry (Abdel Sabour et al., 2008). To select the best alternative in such a system, besides the expected value of alternatives other economical and operational risk indicators should also be considered in the evaluation process.

One of the earliest studies on incorporating uncertainties in calculation of the COGS is the work by Dowd (1976). He developed a stochastic dynamic programming model in which price uncertainty was modeled as a stochastic Markov process. Despite some operational simplifications considered in regard with concentrating and refining plant capacities, it seems that Dowd's model has the potential to be extended to a more general model. Krautkraemer (1988) studied the optimal response of the COGS based on anticipated and unanticipated price changes using optimal control theory. He provided some useful theoretical discussions, but his model is not general and does not seem applicable in a real life mining conditions. Recently, McIsaac (2008) and Thompson (2010) employed golden search optimization inside simulation based models considering metal price uncertainty to find a robust fixed cut-off grade and a fixed mining rate for the whole life of the mining operation in metalliferous underground and open pit mining, respectively. However, employing a fixed cut-off grade throughout the whole mining life time will certainly lead to non-optimal operations and misuse of mining, milling, and refining capacities.

The contribution of this paper is to propose a multi-criteria ranking system to select an optimum COGS, incorporating geological and metal price uncertainties while considering the operating flexibility to abandon the mine early under adverse economic conditions. In this regard, the Lane comprehensive algorithm (Lane, 1988) is used to generate technically feasible alternative COGSs. The price and geological uncertainties are quantified using the stochastic process and geostatistical simulations, respectively. The Least Squares Monte Carlo (LSM) RO valuation model is applied to valuate alternative strategies. Also, the usefulness of the proposed methodology and its sensitivity to the estimated parameters of the price stochastic process are investigated. In the next sections, the mechanism of the employed ranking system adapted for selection of the COGS is outlined and applied to an Iranian gold mine under price and geological uncertainties.

Methodology

In this paper to enhance the decision making process under uncertainty, a multi-criteria ranking system is proposed for selection of the cut-off grade strategy for an open pit mining operation, while integrating geological and market uncertainties and the operating flexibility to close the mine early. This selection system is based on multiple value statistics and cash flow characteristics incorporating a value of management flexibility in reacting to the new information. Fig. 2 shows the employed methodology in this study. This contains five main steps as follows: (1) modeling of metal price uncertainty using stochastic processes; (2) modeling of geological uncertainty using a spatial stochastic simulation method called "conditional simulation." (the uncertainty related to the ore quantity and quality is termed as the geological uncertainty); (3) generating the technically feasible COGSs using the Lane algorithm in conjunction with the simulated equally probable realizations of the ore-body and metal prices; (4) valuation of alternative strategies using the newly developed simulation based RO valuation known as Least Squares