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Determination of the optimum cut-off grades and production scheduling in multi-product open pit mines using imperialist competitive algorithm (ICA)

Sadjad Mohammadi[a,*], Reza Kakaie[a], Mohammad Ataei[a], Eshagh Pourzamani[b]

[a] Faculty of Mining Engineering, Petroleum and Geophysics, Shahrood University of Technology, Shahrood, Iran
[b] Senior expert at the Bureau of Design Supervision, Golgohar Mining and Industry Company, Sirjan, Iran

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ABSTRACT

With regard to the immense importance of cut-off grade in designing and planning open pit mines, optimizing this parameter has considerable effects in mining economic. This paper describes objective function for single metal mines with multi-product. For this purpose, the operation process in mine No.1 of the Golgohar iron mine that produces three types of products (sizing, concentrate and pellet) for sales is used to model objective function. Then the Imperialist Competitive Algorithm (ICA) has been utilized to find out the optimum cut-off grades. Consequently, the optimum cut-off grades has been calculated between 40.5 and 47.5% and net present value has been obtained 18,142 billion Rial. In addition, production scheduling is carried out for five years mining plan pushback. Therefore, the average stripping ratio has been determined 1.41. The result shows that by stockpiling low-grade ore, concentrate plant can be fed by maximum capacity for one year addition to the primary plan.

1. Introduction

In open pit mines, cut-off grade is used to discriminate ore from waste. It is one of the most crucial decisions that must be faced by mine engineers. If the mineral grade is equal to or above cut-off grade, the material is classified as ore and if the grade of mineral is less than the cut-off grade, the material is classified as waste. Depending upon the mining method, waste is either left in situ or sent to the waste dumps, whereas ore is sent to the treatment plant for further processing and eventual sale (Taylor, 1985). Cut-off grades also are used to decide whether material should be stockpiled for future processing or processed immediately (Rendu, 2009).

Due to the dependency of the many economical and operational parameters to the cut-off grade, it is one of the most critical factors in open pit mining. Hence optimizing cut-off grade has several results in the economy, designing and planning of operation. On the other hand, cut-off grade affects production planning through its influence on the ore quantity. Therefore, some researchers take cut-off grade as an internal decision variable in their production scheduling schemes (Wang, 2008). Thereby optimizing the cut-of grades and determining the production scheduling based on it are key problems in mining, management and planning and involve complex analysis and scientific calculation.

From 1954 to now many theories for this subject has presented and various algorithms have used to solve this problem. The basic algorithm to determine the cut-off grades that maximize the NPV of an operation subject to mining, milling, and refining capacities was proposed by Lane (Lane, 1964, 1988). After Lane's algorithm, other researchers have been considered two points, using various optimization methods based on this theory or evaluate the role of various factors in cut-off grade.

Ataei and Osanloo developed a method to find out the optimum cut-off grade for multiple metal deposits. First, they defined objective function for multiple metal deposits and then they used golden section search method and equivalent factor to solve the optimization problem (Ataei and Osanloo, 2003; Osanloo and Ataei, 2003). Among recent researches, the major contribution is belong to Asad's efforts. Asad (2005) modified Lane's algorithm for cut-off grade optimization of two-mineral deposits with an option to stockpile. Then he presented a model by combining impact of economical parameters, escalation and stockpiling options into the optimization model of cut-off grade (Asad, 2011). Bascetin and Nieto (2007) proposed a new method for determination of cut-off grade strategy based on the Lane's algorithm by adding an optimization factor in the generalized reduced gradient algorithm to maximize the NPV. Rashidinejad et al. (2008) presented a model for optimum cut-off grade that not only relies on economical

* Corresponding author.
E-mail addresses: sadjadmohammadi@yahoo.com, sadjadmohammadi@shahroodut.ac.ir (S. Mohammadi), R_kakaie@shahroodut.ac.ir (R. Kakaie), ataei@shahroodut.ac.ir (M. Ataei), eshagh_pourzamani@yahoo.com (E. Pourzamani).

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aspect but also minimizes the form of acid mine drainage elimination or mitigation against the approach of postponing the restoration/reclamation activities at the end of the project's life. Li and Yang (2012) modeled the problem of the cut-off grade optimization as a multistage stochastic programming issue. In this proposed stochastic programming model, each ore grade in a given ore body is a random variable following a distribution. Moreover, they constructed a mathematical model for selecting an optimum cut-off grade function, which aimed at the maximization of total present value of an open pit. Barr (2012) used the stochastic dynamic method to define the objective function to determine optimum cut-off grade for single metal and multi metal deposit under price uncertainty. Abdollahisharif et al. (2012) modified Lane's method in order to incorporate variable processing capacities in the algorithm. Azimi et al. (2013) utilized multi-criteria ranking system to select cut-off grade strategy under metal price and geological uncertainties. Thompson and Barr (2014) employed a new real options model for determining the optimal cut-off grade of ore under stochastic prices. Yasrebi et al. (2015) proposed a modified optimum cut-off grade model in order to maximize the profit value of mining project. They employed the non-linear programming method to solve their models. Rahimi and Ghasemzadeh (2015) developed a model for determining the optimum cut-off grades policy in which intended the bio-heap leaching method with their capital costs and associated environmental considerations. In addition, their model considered the recovery of processing methods as variable.

Despite the existence of a lot of research and studies on this field, up to now, no study has been carried out to determine optimum cut-off grade for single metal with multi-product. Whereas the majority of open pit mines around the world, it produces different types of product. In addition, in a few studies, researches, design and planning of open pit mines, the production scheduling based on the optimum cut-off grades has been considered and conducted. Regarding to these deficiencies and shortcomings, this paper develops an objective function for optimizing cut-off grade in multi products mines and presents production scheduling based on it. Other innovation of this paper is in which a newest and easier meta-heuristic algorithm is used. For this purpose, mine No.1 of the Golgohar iron mine has been considered.

Golgohar Mining and Industry Company is the biggest iron ore mine in Iran and produces three types of products including sizing ore, concentrate and pellet. Therefore, at first cost, revenue and cash flow equations based on the situation of this mine, were determined and then objective function for determination of optimum cut-off grade based on the maximizing the NPV of future cash flow was defined. Due to the complexity of the objective function, ICA was used to find out optimum cut off grades. This method was carried out for five years production plans to determine the optimum cut-off grade strategy, amount of material that must be sent to each unit, amount of selling product, cash flow and total NPV based on the future cash flow.

2. Objective function

Fig. 1 shows the operation process of mine No.1 of the Golgohar. As can be seen from this figure, the mine is capable to put on the markets three types of products including sizing (the size 0–6, 6–12 and 12–25 mm), concentrate and pellet. Producing and selling each product is under a given conditions. For that reason, for selection of ore that must sent to the crushers and concentrate plant or sizing unit, the priority is to provide the maximum feed for concentrate plant. If feed were over than maximum concentrate plant capacity and have average grade equal or higher than 57%, will be sent to sizing unit. It should be noted that the maximum capacity of sizing unit is 1 million tons and this capacity is another constraint in operation. Likewise in the selecting of selling concentrate or sending concentrate to pelletizing plant, providing maximum feed for pelletizing plant has higher priority and the amount of over concentrate than pelletizing plant capacity will be sold. Table 1 shows the parameters which were used to define cost, revenue and operation cash flow and also objective function.

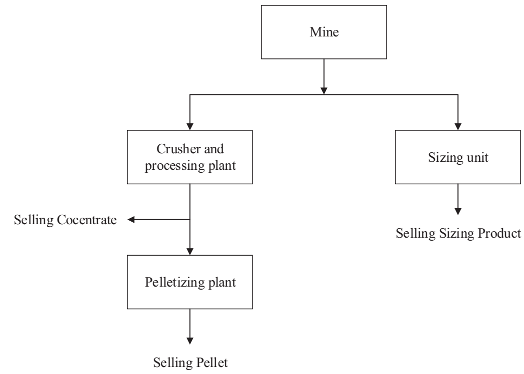

Fig. 1. Operation process in mine No. 1 of Golgohar.

Table 1
The notation of the objective functions.

Symbol	Definition	Unit
Q_m	Material mined	ton
Q_c	Ore Processed	ton
Q_{con}	Concentrate produced	ton
Q_p	Pellet produced	ton
Q_{gr}	Ore sizing produced	ton
M	Mining capacity	ton/year
C	Concentrate plant capacity	ton/year
P	Palletizing capacity	ton/year
α	A part of ore that sent to concentrate plant	–
β	A part of concentrate that sent to pelletizing plant	–
P_p	Pellet price	Rial/ton
P_c	Concentrate price	Rial/ton
P_{gr}	Ore sizing price	Rial/ton
C_m	Mining cost	Rial/ton
C_c	Processing cost	Rial/ton
C_p	Pelletizing cost	Rial/ton
C_{gr}	Ore sizing cost	Rial/ton
f	Fixed cost	Rial/year
T	Years of production	Year
y_c	Recovery of processing	%
d	Discount rate	%

As described before, mining company produces three types of products; therefore, the revenue of each of them can be defined as follow:

$$R_1 = P_p Q_p \tag{1}$$

$$R_2 = P_{gr}(1-\alpha)Q_c \tag{2}$$

$$R_3 = P_c(1-\beta)Q_{con} \tag{3}$$

On the other hand, there are five forms of cost including mining, concentrating, pelletizing, sizing and fix cost. Equations for each of them are shown in below respectively:

$$T_1 = C_m Q_m \tag{4}$$

$$T_2 = C_c \alpha Q_c \tag{5}$$

$$T_3 = C_p Q_p \tag{6}$$

$$T_4 = C_{gr}(1-\alpha)Q_c \tag{7}$$

$$T_5 = fT \tag{8}$$

By using the revenue and the cost, the operation cash flow (profit) can be defined as:

$$P = \sum_{i=1}^{3} R_i - \sum_{i=1}^{5} T_i \tag{9}$$

By substituting the cost and revenue in the Eq. (9), cash flow will be