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A new algorithm to determine optimum cut-off grades considering technical, economical, environmental and social aspects

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ABSTRACT

Optimum cut-off grades with different types of objective functions are determined by optimization algorithms which recognized as the one of the basis of sustainable development indicators of mining. As different mineral processing methods are applied in mines, it is very essential to choose the most appropriate cut-off grades determination algorithm. The current paper is going to analyze the bioheap leaching method and their associated environmental considerations on optimum cut-off grades policy. Remarking the importance of capital costs, these costs are evaluated in the model. Since the recovery of processing methods are changed based upon copper content, the recovery is considered variable in determining optimum cut-off grades. Presented model is evaluated in *Sungun Copper Mine* where the hydrometallurgical tests confirm the possibility of using bioheap leaching method to extract copper from its sulfide ores. It is observed that using bio-heap leaching method for low grade copper ores is subjected not only to improve the NPV of copper mines but also to decrease the adverse environmental impacts and produce sustainable results from mining activities.

1. Introduction

Sustainable development basis are being increasingly applied by mining companies and there is a balance between the cut-off grade determination and sustainable mining practice (Franks et al., 2011; Uqaili et al., 2012). In fact, to gain the optimal cut-off grades and maximum NPV, the environmental consideration social impacts must be integrated in the mine design and issues (Osanloo et al., 2008; Asad and Topal., 2011; Mansouri et al., 2014). Optimum cut-off grades determination is counted as one of the main challenges in sustainable development principles of mining and in the first researches it had no consideration about their requirements (Rashidinejad et al., 2008; Li and Chang, 2012; Khodayari and Jafarnejad, 2012).

Environmental, cultural and social parameters are counted as the main factors of sustainable development (Quinn and Snell, 2008). However, these parameters have not been considered in most of the cut-off grades optimization algorithms. Some have just regarded environmental factors (Dagdelen and Kazuhiro, 2007; Gholamnejad, 2008). According to the fact that sustainable development from mining is very important, mine designing and planning should also measure parameters related to it. Thus, a novel optimum cut-off grade model not only relies on economical and technical considerations but also reclamation, environmental and social parameters. This issue completes previous models on optimum cut-off grades.

It is essential to come into consideration recovery variations caused by grade fluctuation in order to calculate optimum cut-off grades. This is led into a considerable reduction of final products because of average grade decrease. In fact; this issue is remarked as one of the specifications of the new algorithm in comparison to the previous algorithms. The recovery amount is always considered fixed in most of these algorithms (Bascetin and Nieto, 2007; He et al., 2009; Johnson et al., 2011). This is also true in capital costs (Fan et al., 2013). Capital costs can differently affect NPV. These costs include mine opening, plants constructions and production infrastructures. Different processing methods increase investment costs and change optimum cut-off grades. Moreover, investment costs positively affect the sustainable development from social points of view (Pearce et al., 2013).

Science and technology development of ore production and the commodity price fluctuation lead to expanding various mineral processing methods. These processing methods have different technical applications in grade ranges. They also affect the optimum cut-off grades for the sake of various operation costs (Dehghani and Ataee-pour, 2012). Practicing different processing methods in cut-off grades algorithms haven't been considered that much. There have been attempts to make optimum cut-off grades model applying different processing methods like hydrometallurgical ones

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(Rendu, 2008, 2009; Asad and Dimitrakopoulos, 2013). This is while, the sustainable development basis have been preserved.

The particular benefits of hydrometallurgical methods have directed them to be exceedingly practiced in copper mines. Some of the specific characteristics of this method have made it be singled out as the main processing method of small mines such as low costs (Dreisinger, 2006; Rahimi et al., 2014) and producing sustainable development (Uqaili et al., 2012). In spite of the benefits, less pollution and the process simplicity of this method (Watling, 2006), its most outstanding weak point is the low production in comparison to pyrometallurgical methods (Schlesinger et al., 2011). As hydrometallurgical methods have lower recovery and low operating and capital costs, it is emphasized to treat low grades ores by them (Gupta, 2006). Holistically, hydrometallurgical methods are practiced along with pyrometallurgical ones in copper mines. Thus, it is very significant to determine optimum cut-off grades of hydrometallurgical and pyrometallurgical methods. One of the most applicable hydrometallurgical methods is heap leaching ones and there are some industrial applications of these methods for sulfide deposits (Sukla et al., 2009; Rahimi et al., 2015).

In case several processing methods are put into practice in copper mines, determining optimum cut-off grades is important from economical, environmental and social aspects (Yang, 2014). Moreover, it is necessary to identify parameters influencing the profitability in mines in order to provide a model determining optimum cut-off grades. Thus, these factors are defined again. Consequently, capital and operating costs of mine and mineral processing methods are contemplated. Next, the modeling of optimum cut-off grades determination is developed with the objective function of NPV maximization. Since there are various mineral processing methods, associated environmental pollutants and social impacts of these methods are reassessed. The effects of grade variations on process recoveries are also profoundly remarked in order to complete modeling. Eventually, the optimum cut-off grades of leaching and concentration methods are calculated by a constrained optimization method and computer programming due to different constraints.

2. Effective parameters

Cut-off grade is the criterion normally used in mining to discriminate between ore and waste (Lane, 1964; 1988). The complete cut-off grades modeling is a very complex engineering subject and requires engineering knowledge and a good understanding of the many issues. It address sustainable development requirements, average grades and process recoveries, marketable product, controlling capacities and project time , capital and operating expenditure in mine design and planning. So, these effective parameters on cut-off grades determination model are described as follow.

2.1. Sustainable development

Although some researchers have defined the concept differently, sustainable development, generally, is the combination of improved socioeconomic development, and enhanced environmental protection. Thus, two aspects of sustainability concept are considered in paper as follow:

2.1.1. Environmental impacts

Sustainable development basis leads to applying the environmentally friendly mining activities. It is very essential to integrate the sustainable development requirements in mines' profitability and optimum cut-off grades (Rodriguez and Rozgonyi, 2004; Mansouri et al., 2014). As the mining and processing activities cause environmental pollutants, it is necessary to identify them. Hence, the environmental pollutants of mines, leaching and concentration methods are classified as below:

(1) Mine waste disposal cost (t_1), (2) Leached waste disposal cost (t_2), (3) Solvent extraction (SX) and Electrowinning (EW) tailing disposal cost (t_3), (4) Concentration tailing disposal cost (t_4), (5) Smelter and Electrorefining tailing disposal cost (t_5), (6) Environmental protection cost of hydrometallurgical processes (t_6), (7) Environmental protection cost of pyrometallurgical processes (t_7), (8) The amount of leached material remained on heap (a_1%), (9) The amount of SX and EW tailing (a_2%), (10) The amount of concentration tailing (a_3%) and (11) The amount of smelter and electrorefining tailing (a_4%). Every process of producing final product can individually produce environmental pollutants. Thus, it seems indispensable to examine environmental costs of these production processes to determine optimum cut-off grades.

2.1.2. Social impacts

Mining is an economic short-term activity with long-term effects. The sustainable development requirements have extended social responsibility of mine stockholders (Mutti et al., 2012). Mining has had an important role in shaping human development not only from a technological perspective, but it has also significantly influenced on working arrangements, lack of safety, child labor, rivalry and internal strife (Laurence, 2011; Hajkowicz et al., 2011). All this is added to the hazardous and unhealthy working conditions of this type of activity and it makes unavoidable costs. There can be no doubt that when it takes place, cut-off grades policy will be changed. There for the social costs indicator in cut-off grades determination algorithm is shown by t_s .

2.2. Average grades and process recoveries

Mineral processing plants are designed based on average grades of feed. It is obvious that the average grades of ore sent to processing plants completely rely on optimum cut-off grades policy. As mines use several processing methods, this policy seems more significant. The average grade of ores sent to leaching ($\bar{a}_H$) and concentration ($\bar{a}_C$) plants are obtained by Eq. (1), in continuous form of grades distribution.

$$\bar{a}_C(g) = \frac{\int_{g^c}^{G} g \times q_i(g)\, dg}{\int_{g^c}^{G} q_i(g)\, dg}, \quad \bar{a}_H(g) = \frac{\int_{g^h}^{g^c} g \times q_i(g) dg}{\int_{g^h}^{g^c} q_i(g) dg} \tag{1}$$

These relations are defined in discounted form of grade distribution of mines based on ore tonnage as the following:

$$\bar{a}_C(g) = \frac{1}{2}\left[\left(\frac{\left(g_{up}^{\zeta(g^c)}\right)^2 - (g^c)^2}{g_{up}^{\zeta(g^c)} - g_{down}^{\zeta(g^c)}}\right) \times q_i^{\zeta(g^c)} + \sum_{\zeta=\zeta_{g^c+1}}^{\zeta G} \left(g_{up}^{\zeta} + g_{down}^{\zeta}\right) q_i^{\zeta}\right], \quad \bar{a}_H(g) = \frac{1}{2}\left[\left(\frac{g_{up}^{\zeta(g^h)^2} - g^{h2}}{g_{up}^{\zeta(g^h)} - g_{down}^{\zeta(g^h)}}\right) \times q_i^{\zeta(g^h)} + \sum_{\zeta=\zeta_{g^h+1}}^{\zeta=\zeta_{g^c-1}} (g_{up}^{\zeta} + g_{down}^{\zeta}) \; q_i^{\zeta}(g_{up}^{\zeta} + g_{down}^{\zeta}) q_i^{\zeta} + \left(\frac{(g^c)^2 - g_{down}^{\zeta(g^c)^2}}{g_{up}^{\zeta(g^c)} - g_{down}^{\zeta(g^c)}}\right) q_i^{\zeta(g^c)}\right] \tag{2}$$