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Strategic mining options optimization: Open pit mining, underground mining or both

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ABSTRACT

Near-surface deposits that extend to considerable depths are often amenable to both open pit mining and/or underground mining. This paper investigates the strategy of mining options for an orebody using a Mixed Integer Linear Programming (MILP) optimization framework. The MILP formulation maximizes the Net Present Value (NPV) of the reserve when extracted with (i) open pit mining, (ii) underground mining, and (iii) concurrent open pit and underground mining. Comparatively, implementing open pit mining generates a higher NPV than underground mining. However considering the investment required for these mining options, underground mining generates a better return on investment than open pit mining. Also, in the concurrent open pit and underground mining scenario, the optimizer prefers extracting blocks using open pit mining. Although the underground mine could access ore sooner, the mining cost differential for open pit mining is more than compensated for by the discounting benefits associated with earlier underground mining.

1. Introduction

Mining is the process of extracting a beneficial naturally occurring resource from the earth [1,2] and historical assessment of mineral resource evaluations has demonstrated the sensitivity of project profitability to decisions based on mine planning. A major aspect of mine planning is the optimization of long-term production scheduling. The aim of long-term production scheduling is to determine the time and sequence of extraction and displacement of ore and waste in order to maximize the overall discounted net revenue from a mine within the existing economic, technical and environmental constraints. Long-term production schedules defines the mining and processing plant capacity, and expansion potential as well as management investment strategy. In mining projects, deviations from optimal mine plans may result in significant financial losses, future financial liabilities, delayed reclamation and resource sterilization.

The problem of optimizing reserve exploitation depends largely on the mining option used in the extraction. Some mineral deposits have orebodies that extend from near the surface to several meters in depth. Such deposits can be amenable to both open pit mining and/or underground mining. Significant value can be generated by rigorously investigating these mining options using optimization tools to arrive at the appropriate strategic plan that maximizes the overall Net Present Value (NPV) of the deposit [3,4]. Open pit mining usually features a relatively lower mining cost, higher stripping ratio and longer time to access ore [5]. Underground mining on the other hand features a higher mining cost, higher grade and earlier access to ore [6–8]. There are currently limited tools or methods to directly optimize this interface.

Current strategic open pit and underground mining interface optimization models have been developed mainly based on determining the transition point or depth between open pit mining and underground mining. The models focus on investigating how an underground operation can be mined after an open pit mine or combined with an existing open pit operation [3,6,9,10]. These models do not have the capacity to consider the full range of underground mining constraints required for selective and bulk mining along with the associated interface challenges. Other open pit to underground transition models are developed based on heuristic algorithms or scenario based analysis with no measure of optimality [11–15]. It is our objective to develop a Mixed Integer Linear Programming (MILP) framework and methodology to evaluate the financial impact of applying different mining options separately or concurrently to extract a given orebody.

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The next section of this paper presents the mining options problem definition and Section 3 outlines a MILP model framework for strategic mining options optimization. Section 4 covers the modeling and material flow network of the mining options problem. Details of a numerical experiment to be conducted are outlined in Section 5 and the application of the MILP formulation to a case study is discussed in Section 6. The paper concludes in Section 7.

2. Mining options problem

A strategic plan is to be developed for a moderate dipping gold-silver-copper orebody that is amenable to both open pit and underground mining. It is required that in addition to these mining options, a combined case of concurrent open pit and underground mining is investigated as well. From preliminary underground mining studies, a selective underground mining method known as long hole open stoping was identified as a potentially viable underground mining method. The production schedule for a combined open pit and underground mining scenario requires that both mining options compete for the same reserve during optimization. The problem presented here involves scheduling of N different ore and waste blocks: (i) within the final pit limit over T different periods of extraction–OP mining, (ii) within the economic stope outlines over T different periods of extraction–OS mining, and (iii) within the combined final pit limit and economic stope outlines over T different periods of extraction–COPOS mining. The schedule should maximize the NPV of the operation subject to a variety of physical, technical and economic constraints. Fig. 1 shows a schematic diagram of the problem definition. A MILP formulation was developed for this strategic mining options optimization study. This research forms part of a feasibility study undertaken to strategize the extraction of the gold-silver-copper orebody.

3. Integrated MILP model for OP, OS and COPOS mining

The basic problem of concern can be simplified as finding the time and sequence of extraction of ore and waste blocks to be removed from the predefined open pit and/or open stopes outlines and their respective destinations over the mine life so that the NPV of the operation is maximized. The production schedule is subject to a variety of technical, physical and economic constraints which enforce the mining extraction sequence, mining and processing capacities, and blending requirements. The notations used in the formulation have been classified as sets, indices, subscripts, superscripts, parameters, and decision variables.

3.1. Economic block value modeling

The objective function of the MILP model is to maximize the N of the mining operation. This requires that economic block values are defined based on ore parcels which could be mined selectively. The profit generated from mining a block depends on the value of that block and the costs incurred in mining and processing the block. The cost of mining a block is a function of its spatial location. When a mined block is sent to the stockpile prior to processing, then an extra cost of re-handling is applied.

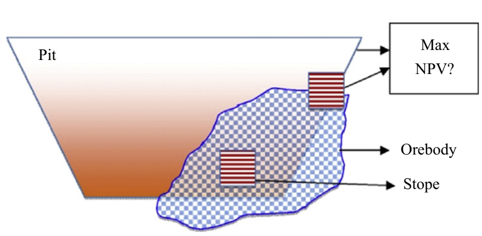

Fig. 1. Schematic representation of the problem definition showing the mining options modified after Ben-Awuah et al. [16].

The discounted economic block value for block k is equal to the discounted revenue generated by selling the final product contained in block k minus all the discounted costs involved in extracting block k and processing it. The discounted economic block value is computed separately for when the block is extracted by open pit mining and when it is extracted by open stope mining. This can be summarized by Eqs. (1)–(6).

Discounted economic block value = discounted revenue-discounted costs.

$$d_k^{op,t} = v_k^t - q_k^{op,t} - l_k^{op,t} \quad (1)$$

$$d_k^{os,t} = v_k^t - q_k^{os,t} \quad (2)$$

The variables in Eqs. (1) and (2) can be decomposed into Eqs. (3)–(6).

$$v_k^t = \sum_{e=1}^{E} o_k \times g_k^e \times r^{e,t} \times (p^{e,t} - cs^{e,t}) - \sum_{e=1}^{E} o_k \times cp^{e,t} \quad (3)$$

$$q_k^{op,t} = (o_k + w_k) \times cm^{op,t} \quad (4)$$

$$l_k^{op,t} = o_k \times rh^{op,t} \quad (5)$$

$$q_k^{os,t} = (o_k + w_k) \times cm^{os,t} \quad (6)$$

where $t \in \{1,\ldots,T\}$ is the index for scheduling periods, $k \in \{1,\ldots,K\}$ index for blocks, $e \in \{1,\ldots,E\}$ index for element of interest in each block, $j \in \{1,\ldots,J\}$ index for phases (pushback), $d_k^{op,t}$ the open pit discounted economic block value generated by extracting block k in period t, $d_k^{os,t}$ the open stope discounted economic block value generated by extracting block k in period t, v_k^t the discounted revenue generated by selling the final product within block k in period t minus the extra discounted cost of mining all the material in block k as ore and processing it, $q_k^{op,t}$ the open pit discounted cost of mining all the material in block k in period t as waste, $l_k^{op,t}$ the open pit discounted cost of re-handling for all material in block k in period t processed from the stockpile, $q_k^{os,t}$ the open stope discounted cost of mining all the material in block k in period t as waste, o_k the ore tonnage in block k, w_k the waste tonnage in block k, g_k^e the average grade of element e in ore portion of block k, $r^{e,t}$ the processing recovery factor for element e, $p^{e,t}$ the price of element e in present value terms per unit of product, $cs^{e,t}$ the selling cost of element e in present value terms per unit of product, $cp^{e,t}$ the extra cost in present value terms per tonne of ore for mining and processing, $cm^{op,t}$ the open pit cost in present value terms of mining a tonne of waste in period t, $rh^{op,t}$ the open pit cost in present value terms of re-handling a tonne of ore in period t, and $cm^{os,t}$ the open stope cost in present value terms of mining a tonne of waste in period t.

3.2. Integrated MILP model objective function

In the proposed integrated MILP model, the formulation is cast to ensure that material can be extracted only once by either of the mining options. The MILP model objective function can be formulated as: (i) maximizing the NPV of the open pit mining operation and (ii) maximizing the NPV of the open stope mining operation. This is represented by Eq. (7). We used the concepts presented in Ben-Awuah et al. [17] as the starting point of our development. The amount of ore processed is controlled by the continuous