Optimization of the Open-pit/Panel Caving Joint Production Plan

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***Abstract*—Today, many open-pit mines are starting to deplete their resources and could be forced to leave the ore in the deepest parts of the pit, which could lead to a loss of possible economical revenue. Therefore, open-pit mines are developing new strategies to extract the mineral via underground mining systems. For massive orebodies, the most profitable extraction methods are those that consider the caving of the rock, in particular, the block/panel caving methods, due to their low operational costs and their high productivity. Methodologies applied to define the optimum decision for transitioning from open pit to underground mines are often limited or biased because they tend to give priority to the open pit operation, analyzing until which phase to extract from the open pit to continue with the underground operation.**

In this paper, a new methodology is proposed to maximize the NPV and the copper fine flow to the plant based on the scheduling sequence. Open-pit and panel caving envelopes are calculated, considering or not a potential crown pillar between them for stability purposes. Subsequently, the block scheduling and NPV maximization of both systems is made, considering operational and geomechanical constraints to analyse their influence on the scheduling.

This methodology has been applied in both synthetic block models and mining scale cases. The production plans, NPV variations and block scheduling are analysed based on the different groups of parameters. Results indicate that the transition period and production plans, where both mining systems extract mineral together and the remaining periods where panel caving is the only system extracting ore, are heavily influenced by the caving sequence and the constraints related to the underground mine.

Using this procedure, the economic benefit of the panel caving mine and the feasibility of the different sequences that can be applied to the model can be studied. This model will allow mine planners to define the best strategy for the production capacity, sequencing and geomechanical decisions, while maximizing NPV and the copper fine sent to the plant, ensuring the safety of the workers.

I. Introduction

Transition is defined as the process of passing from one method of exploitation to another. This process can be triggered by the economic unfeasibility of extracting ore through the first method and thus perceive positive economic benefits of exploitation by another method. The most common example is the transition from an open pit (where grades decrease and mining costs increase as the mine becomes deeper) to an underground mine (allowing the extraction of mineral at a lower cost).

A common case corresponds to the transition to self-supported underground mines. This case is relatively simpler than caving operations because geomechanical constraints allow partially decoupling of the open pit and underground operations. However, operational constraints for scheduling in this case are more complex due to precedence between pillars and stopes for different activities [1]. Therefore, some authors have studied the problem of optimizing economic envelopes. [2] and [3] propose an algorithm that is applied in non-massive underground methods. The algorithm works by sequentially evaluating different floors for economic envelopes and, thus, obtain the sequence combination with the greatest economic benefit.

For massive caving methods, such as panel caving, a similar approach to the one described was proposed in [4], which included the incorporation of crown pillars and dilution using the Laubscher's method. For this caving methods also, optimization of the simultaneous production scheduling was modelled by [5], who considered different expansions and sectors for the open pit and the underground method, which have already been sequenced in a compatible way. Optimization models for scheduling have also been proposed for panel caving, for example, [6] showed, through the application of precedence and capacity constraints, the importance of selecting the optimum starting point for the underground mine, which would affect the value of the project. Due to the large number of variables and constraints, simplification can be achieved by using material strata [7], where each strata is susceptible to be extracted by open-pit or underground. Through the use of vertical extraction constraints, a strata is fixed from which only the upper strata can be extracted by open-pit and the lower strata by underground. Another approach is to group extraction points into clusters [8], based on column tonnage, mean grade, and physical location. This reduces the number of decision variables and the constraints associated with the model and, thus, reducing the computation time.

The objective of this work is to establish a methodology for the optimization of joint production plans of an open pit and an underground panel caving operation, at the block model level.

The model aims to generate the highest NPV and schedule for each mine. A mathematical program modelling both operations and their potential interactions is proposed and applied to case studies.

II. METHODOLOGY

The proposed model considers two important stages in its formulation: the calculation of economic envelopes and the block-by-block scheduling of these envelopes.

A. Determination of economic envelopes

This stage consists of the delimitation of the block model in 2 envelopes corresponding to the Open-Pit envelope and the Panel Caving envelope. The technical/economic parameters that define these regions of the model must be established, including metal prices, mine costs, plant and refining costs, and metallurgical recovery. For the case of the Panel Caving envelope, the development cost per area to be applied to the blocks at the base of the envelope and the required minimum column height must also be included. There are two possible ways to define the dimensions of each of these zones: predefine a floor for each envelope or apply an optimum floor algorithm, in this case Open-pit/Panel Caving, with the grades diluted in the latter.

B. Block-by-block scheduling

Two types of variables are considered:

$$x_{itd}^{OP} = \begin{cases} 1, & \text{if block i is extracted through OP by period t} \\ & \text{to destination d} \\ 0, & \text{otherwise} \end{cases}$$

$$x_{itd}^{UG} = \begin{cases} 1, & \text{if block i is extracted through UG by period t} \\ 0, & \text{otherwise} \end{cases}$$

The interpretation of variable x_{it} is by time-period, that is $x_{it} = 1$ if and only if block i has been extracted (and processed) at some period with $1 \leq s \leq t$. It is useful to introduce the following auxiliary variables for $i \epsilon B$: $\Delta x_{i1} = x_{i1}$, and $\Delta x_{it} = x_{it} - x_{(it-1)}$ for t = 2, 3, ..., T. Then, $x_{it} = \sum_{s=1}^{t} \Delta x_{is}$ and $\Delta x_{i1} = 1$ if, and only if, block i is extracted exactly at time-period t. Here, destination 1, 2 and 3 correspond to dump, plant and stockpile, respectively. The objective function which maximizes the NPV is as follows:

$$\max \sum_{t \epsilon T} \left(\frac{1}{1+\delta}\right) \left(\left(\sum_{i \epsilon B_{ug}} (v_i^{ug} - c_i^{ug}) \Delta x_{it}^{ug} \right)_1 - \left(\sum_{p \epsilon P_{ug}} C_{dev} Pev_p \right)_2 + \left(\sum_{d \epsilon D_{op}} \sum_{i \epsilon B_{op}} (v_{id}^{op} - c_{id}^{op}) \Delta x_{it}^{op} \right)_3 + \left(\sum_{s \epsilon S_{op}} (v_s - c_s) f_{st} \right)_4 \right)$$

Where δ represents the discount rate, v_i^{ug} and c_i^{ug} represent the value and cost of block i in the underground mine, C_{dev} corresponds to the deviation penalty cost and Pev_p the production deviation from drawpoint p, v_{id}^{OP} and c_{id}^{OP} represent the value and cost of block i when sent to destination d in the open-pit mine, and v_s and c_s correspond to the value and cost of the flow f_{st} of material sent from the stockpile to the plant.

Here, each term of the formula corresponds to:

1) Underground profit.
2) Drawpoint production deviation penalty.
3) Open-pit profit.
4) Stockpile profit.

Subject to the following constraints, depending on the part of the model that is considered :

1) Open-pit constraints:

- Mine/plant capacities.
- Precedences.
- Blending.
- Stockpiles capacities.

2) Underground constraints:

- Mine capacity.
- Crosscut capacity.
- Production and development rates.
- Horizontal, vertical and caveback precedences.
- Draw rates.

3) Transition constraints:

- Maximum number of periods for joint production.

III. CASE STUDY

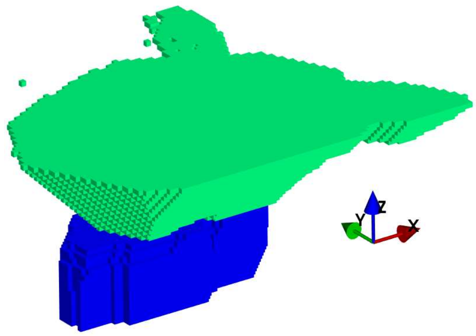
To exemplify the method, a block model of copper and gold, with blocks of size 20x20x20 [m] was used. The model has an average copper grade of 0.13% and an average gold grade of 2.35 [ppm]. For this study, two options were evaluated: a sequential method, where each mine's scheduling is optimized separately to, subsequently, manually create the transition, while the second option was an integrated approach, where the optimization evaluated both options at the same time. For the latter, two different approaches were made: with a crown pillar of 200 [m] and with a direct contact between the envelopes. Each approach was evaluated using two different initial caving points in the underground layout: Points A and B (Figures 1a and 1b).

IV. RESULTS

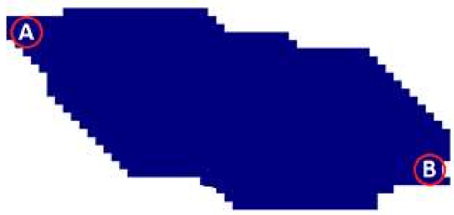
The resulting NPV and transition periods are shown in Figure 2, while the optimized production plan for the caving sequence starting at A with no crown pillar is shown in Figure 3.

In each case, the underground envelope is extracted completely given its high grades and the penalty in the drawpoint production, forcing these to always be in production. The crown pillar has no major influence over the transition period, dude to the higher grades being in the upper section of the open-pit. Because the crown pillar only reduces the size of the open-pit envelope, keeping the size of the underground, and the grades are decreasing in depth, the upper blocks are extracted prior to the extraction of the underground because of the high benefits it delivers.

Case A starts earlier because it has a higher concentration of copper and gold in its vicinity. On the other hand, Case



(a) Envelopes to be scheduled



(b) Initiation points

Case study	Crown Pillar	Starting Point	Transition period [year]	NPV [MUSD]	NPV starting at period 30 [MUSD]
Integrated	No CP	A	35	1,298	489
		B	41	1,291	367
	200 m	A	21	1,074	449*
		B	21	1,072	441*
Sequential	No CP	A	50	1,289	342
		B	50	1,288	304

Fig. 2: Schedule summary for the case study (*NPV evaluated starting at period 20)

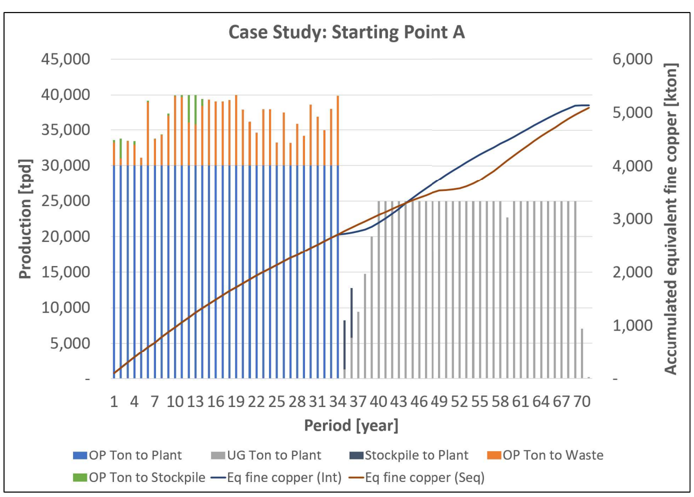


Fig. 3: Production plan with caving sequence starting at A

B has a lower concentration, which decreases the influence in the transition period.

V. Conclusion

This model allows an evaluation of the transition alternative from the beginning or for already operating mines, using block models with a previous extraction. The model extends previous efforts, which were either limited in scope or could not work at a block level. The model not only allows the user to determine the optimal transition period but also provides the block scheduling with the maximum copper/gold production and NPV. This will allow planners to have a guide for the evaluation of the transition for any type of mineralization, given its versatility to be able to evaluate different types of sequences in both the open pit and underground. Furthermore, it allows the addition of ramps and more stocks in the open-pit model, tools that were not evaluated due to the considerable increase in computation time in previous studies.

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