Long-Term Production Scheduling in an Open-Pit to Panel Caving Transition Context

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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. 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, which does not necessarily result in an optimum NPV.

In this paper, a new methodology is proposed to maximize the NPV based on the scheduling sequence. Open-pit and panel caving envelopes are calculated, considering 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 NPV 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 ensuring the safety of the workers.

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 (King et al, 2016). Therefore, some authors have studied the problem of optimizing economic envelopes. Bakhtavar et al (2009) and Bakhtavar et al (2012) 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 Julio (2015), 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 Epstein et al (2012), 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, Smoljanovic et al, (2011) 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 (Newman et al, 2013), 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 (Yashar et al, 2013), 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.

Palabora undertook a joint production (joint production includes the ramp-up of the underground mine) by extracting its main ramp, achieving a production of 16,000 [tpd] (Moss et al, 2006). However, this involved a constant study of the open-pit geomechanical conditions and, therefore, it is recommended not to exceed the joint extraction for more than 6 months (Visser, 2006).

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.

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.

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.

Block-by-block scheduling

For the block-by-block scheduling the following variables are defined:

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

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

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 periods with 1 ≤ s ≤ t. It is useful to introduce the following auxiliary variables for i ∈ B: $\Delta x_{i1} = x_{i1}$, and $\Delta x_{it} = x_{it} - x_{it-1}$ for t = 2, 3,..., T .Then, $x_{it} = \sum_{s=1}^{t} \Delta x_{it}$ and $\Delta x_{it} = 1$ 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:

$$\max \sum_{t\epsilon T} \left(\frac{1}{1+\delta}\right)^t \left(\begin{array}{c} \left(\sum_{i\epsilon B_{UG}} (v_i^{UG} - c_i^{UG}) \Delta x_{it}^{UG} \right) - \sum_{p\epsilon P_{UG}} C_{dev} Pev_p + \\ \left(\sum_{d\epsilon D_{OP}} \sum_{i\epsilon B_{OP}} (v_{id}^{OP} - c_{id}^{OP}) \Delta x_{itd}^{OP} \right) + \sum_{s\epsilon S_{OP}} (v_s - c_s) f_{st} \end{array} \right) \quad (1)$$

where, B_{UG} and B_{OP} represents the set of blocks in the underground and open-pit envelopes. The variables v_b^{OP}, v_b^{UG} represent the block incomes and c_b^{OP}, c_b^{UG} the mine and processing costs for open-pit and PC respectively. Let $p \in P_{UG}$ represent the set of drawpoints in the underground mine, C_{dev} the deviation unit cost for deficient production and Pev_p the deficient production of drawpoint p compared to the production target. Let D_{OP} represent the set of destinies in the open-pit mine and

$S_{OP} \in D_{OP}$ the set of stocks in the open-pit model. Let v_s and c_s be the income and cost of sending material from the stocks to plant. Finally, δ represents the discount rate and T the periods to be evaluated in the schedule.

Open-pit modelling

In this section we describe the modelling corresponding to the open-pit operation, which considers three main destinations: dump, plant and stockpile. The following parameters are defined:

CP_{mine}^{OP} and CP_{plant}^{OP} are the production capacity for the mine and the plant

CP_s^{OP} is the stockpile capacity for stock s

$S(i) \in B_{OP}$ is the set of predecessor blocks of block i

PUL and PLL are the upper and lower limits for metal grade in the blocks for their treatment in the plant

g_i and w_i are the grade and total tonnage of block i,

m_i is the metal content in block i

AG_s represents the average grade of the stockpile s, and

L_g^S and U_g^S represent the lower and upper limits of grades that can enter the stockpile.

Then,

$$\sum_{i \varepsilon B_{OP}} w_i \Delta x_{it1}^{OP} + \sum_{i \varepsilon B_{OP}} w_i \Delta x_{it2}^{OP} + \sum_{s \varepsilon S_{OP}} f_{st} \leq CP_{mine}^{OP} \qquad \forall\, t \in T \qquad (2)$$

$$\sum_{i \varepsilon B_{OP}} w_i \Delta x_{it2}^{OP} + \sum_{s \varepsilon S_{OP}} f_{st} \leq CP_{plant}^{OP} \qquad \forall\, t \in T \qquad (3)$$

$$\sum_{t^* \leq t} \left(\left(\sum_{i \epsilon B_{OP}} w_i \Delta x_{it^*s}^{OP} \right) - f_{st^*} \right) \leq CP_s^{OP} \qquad \forall s \in S_{OP}, \forall\, t \in T \qquad (4)$$

$$\Delta x_{itd}^{OP} \leq \sum_{t^* \leq t} \sum_{d \epsilon D_{OP}} \Delta x_{jt^*d}^{OP} \qquad \forall i \in B_{OP}, \forall j \in S(i), \forall t \in T \qquad (5)$$

$$\left(\sum_{i \epsilon B_{OP}} (PUL - g_i) * w_i \Delta x_{itd}^{OP} \right) + \sum_{s \varepsilon S} (PUL - AG_s) * f_{st} \geq 0 \qquad \forall\, t \in T \qquad (6)$$

$$\left(\sum_{i \epsilon B_{OP}} (g_i - PLL) * w_i \Delta x_{itd}^{OP} \right) + \sum_{s \varepsilon S} (AG_s - PLL) * f_{st} \geq 0 \qquad \forall\, t \in T \qquad (7)$$

$$L_g^S * \sum_{t^* \leq t} \sum_{i \epsilon B_{OP}} w_i \Delta x_{it^*s}^{OP} \leq \sum_{t^* \leq t} \sum_{i \epsilon B_{OP}} m_i \Delta x_{it^*s}^{OP} \leq U_g^S * \sum_{t^* \leq t} \sum_{i \epsilon B^{OP}} w_i \Delta x_{it^*s}^{OP} \qquad \forall s \in S_{OP} \qquad (8)$$

Constraints (2), (3) and (4) impose the maximum mine, processing and stockpile capacity. Constraint (5) imposes the precedence constraints for the blocks. Constraints (6) and (7) limits the metal grades that can be sent to the plant. Constraint (8) limits the metal grades that can be sent to stockpile.

Panel Caving modelling

The underground part of model considers a single destination, but with restrictions of a more operational and geomechanical nature. Here, CP^{UG} and CC_C are the production capacities of the whole underground mine and the capacity per crosscut. If $B_{UG}^{C} \in B_{UG}$ are the set of blocks that belong to crosscut c, then

$$\sum_{i\varepsilon B_{UG}} w_i \Delta x_{it}^{UG} \leq CP^{UG} \qquad \forall\, t \in T \qquad (9)$$

$$\sum_{i\varepsilon B_{UG}^{C}} w_i \Delta x_{it}^{UG} \leq CC_c \qquad \forall\, t \in T \qquad (10)$$

$$\Delta x_{it}^{ug} \leq \sum_{s\leq t} \Delta x_{js}^{ug} \qquad \forall i \in B_{UG}, \forall j \in S(i), \forall t \in T \qquad (11)$$

Constraints (9) and (10) impose the maximum mine capacity for the underground mine and for the crosscuts. Constraint (11) imposes the precedence constraints for the blocks in the underground mine. These set of precedence constraints include both vertical precedence, the 45° caving angle precedences and horizontal precedences in the production level.

Modelling of the transition

The transition part of the model abstracts the interaction between the variables of both models. Here, NEB_t represents the necessary blocks to be extracted in the open-pit mine to let the production of the underground mine start. It is equal to 1, when the required number of blocks extracted is met by period t, and is equal to 0 when not. ML represents the maximum number of periods where mines may be producing together and JP_t equals 1 if the mines did produce together in period t. This parameter can be set to zero if no periods of overlapping are allowed. Then,

$$NBE_t \geq \Delta x_{it}^{ug} \qquad \forall\, t \in T \qquad (12)$$

$$\sum_{t\varepsilon T} JP_t \leq ML \qquad \forall\, t \in T \qquad (13)$$

$$\sum_{t^*\leq t} \left(\left(\sum_{i\epsilon B_{OP}} w_i \Delta x_{it^*s}^{OP} \right) - f_{st^*} \right) \leq CP_s^{OP} \qquad \forall i \in B_{UG}, \forall j \in S(i), \forall t \in T \qquad (14)$$

$$NBE_t \in \{0,1\}, \qquad JP_t \in \{0,1\}$$

CASE STUDY

Block Model description

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]. The economical/technical parameters are shown in Table 1.

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 (Fig. 1).

Table 1 Open-pit and Panel Caving envelope parameters

Open-pit		Panel Caving	
Parameter	**Value**	**Parameter**	**Value**
Mine cost [US$/t]	5	Mine cost [US$/t]	8
Plant cost [US$/t]	10	Plant cost [US$/t]	10
Copper refining cost [US$/lb]	0.35	Copper refining cost [US$/lb]	0.35
Gold refining cost [US$/lb]	15	Gold refining cost [US$/lb]	15
Mine capacity [tpd]	40,000	Mine capacity [tpd]	25,000
Plant capacity [tpd]	30,000	Crosscut capacity [tpd]	6,000
Metallurgical recovery [%]	85	Metallurgical recovery [%]	85
Stock capacity [t]	1,000,000	Development cost [US$/m2]	3,000
Stock average copper grade [%]	0.5	Development rate [m2/year]	20,000
Initial investment [MUS$]	87.64	Ramp cost [US$/m]	4,000
		Initial/Final draw rate [t/d/m2]	0.3/0.7

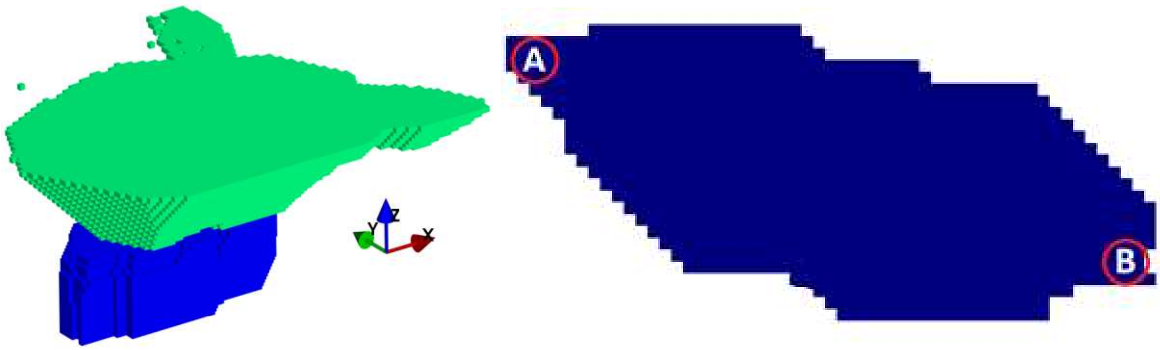

Figure 1 Envelopes to be scheduled, and the 2 different initiation points for the caving sequence (DOPPLER).

RESULTS AND DISCUSSION

The resulting NPV and transition periods are shown in Table 2.

Table 2 Case study: schedule summary for both crown pillar cases

Caving sequence	Parameter	Sequential	CP 200 [m]	Without CP
Point A	NPV [MUS$]	1,497.9	1,176.2	1,505.9
	Transition Period [year]	48	22	47
	OP Extracted Tonnage [Mt]	671.6	278.8	656.9
	UG Extracted Tonnage [Mt]	289.9	289.9	289.9
	Fine copper [Kt]	4,660.7	3,103.9	4,614.9
	Fine gold [t]	207,7	134.7	205.4
Point B	NPV [MUS$]	1,495.7	1,155.2	1,507.9
	Transition Period [year]	48	22	44
	OP Extracted Tonnage [Mt]	671.6	279.3	614.3
	UG Extracted Tonnage [Mt]	289.9	289.9	287.7
	Fine copper [Kt]	4,660.7	3,106.5	4,483.1
	Fine gold [Kg]	207.7	134.6	199.3

Examples of the production plans for the variant without crown pillar can be seen in Figure 2 and Figure 3.

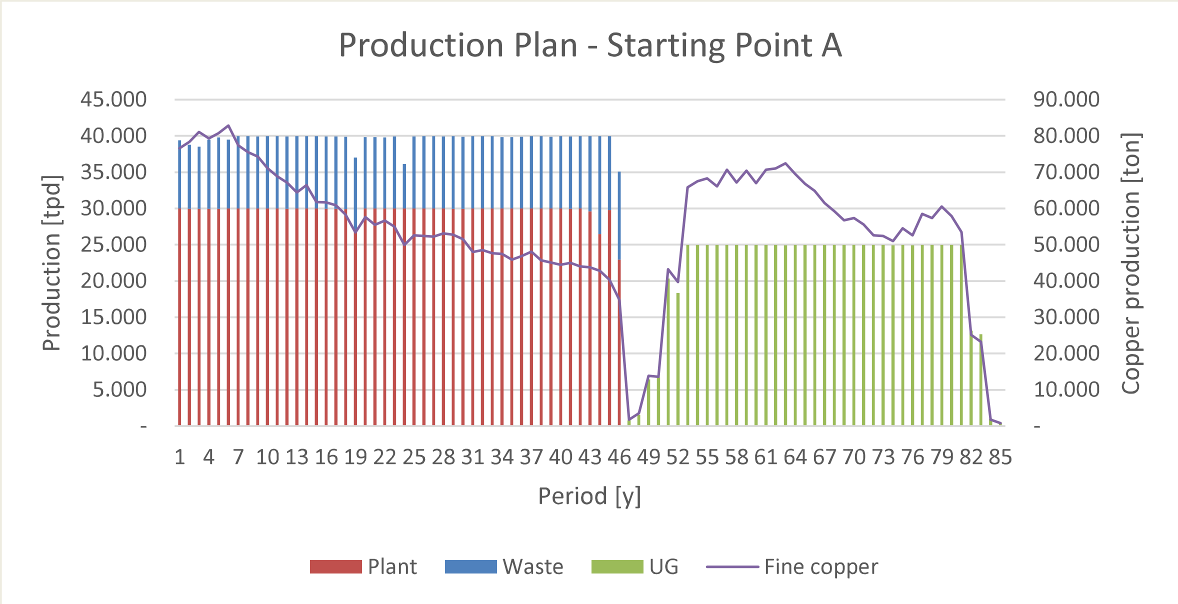

Figure 2 Production plan with caving sequence starting at point A

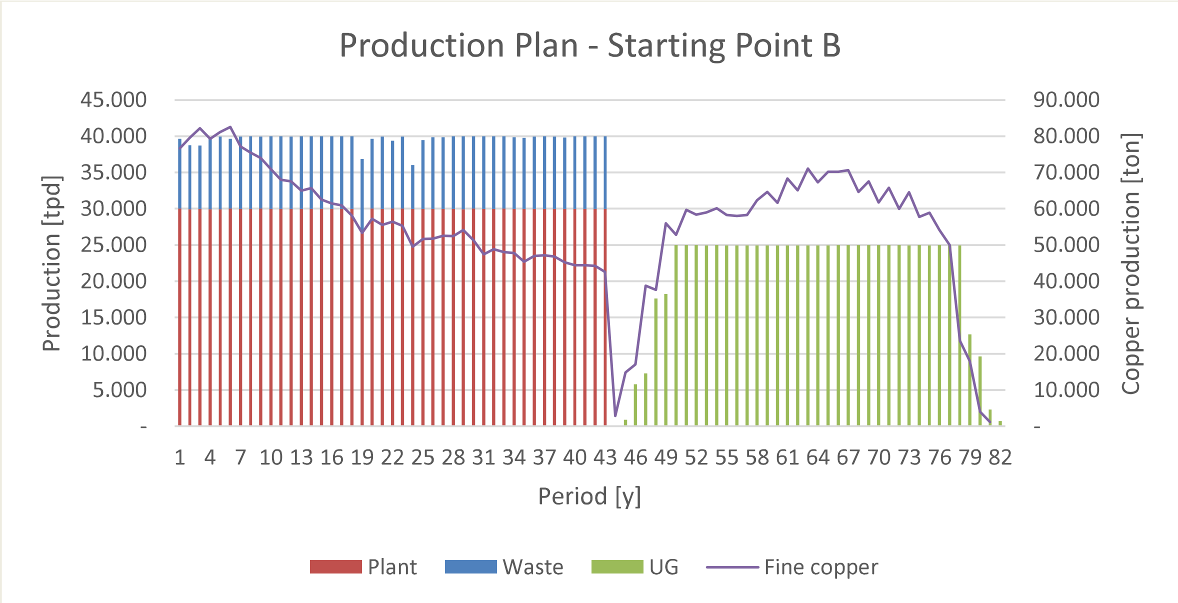

Figure 3 Production plan with caving sequence starting at point B

Case B shows a transition period equivalent to year 44 while case A corresponds to year 47. This is because, in case B, the starting point of caving has higher grades at the beginning of extraction. However, areas close to point A have grades higher than those of point B, but their delayed start in the first years of production means that they do not have a greater impact on the NPV. Significant fluctuations are observed in the material sent to plant in case A for the last periods of the open-pit mine.

In Case B, before carrying out the transition, the fall in production of fine copper is less drastic than Case A, in addition to having a constant production of fine copper during the underground extraction. Also, in Case B, fewer periods are required to return to a constant feed of mineral to the plant. Because to this, increases in treatment costs can be expected: the variations of tonnages and grades sent to the plant may involve significant decreases in the utilization of the plant equipment and increases in the additives required for metal recovery from low grade material.

CONCLUSIONS

We proposed a model to optimize the transition from open pit to panel caving operations. This model allows an evaluation of the transition alternative from the beginning or for already operating mines, allowing simultaneous production and existence of a crown pillar separating both operations. The model is novel because it extends previous efforts, which were either limited in scope (assume given sequences or consider only economic envelopes) or could not work at a block level. The model not only allows the user to determine the optimal transition period but also provides block scheduling and NPV maximizing production schedules. 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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