A Novel Approach to Estimate the Gap Between the Middle and Short-Term Plans

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ABSTRACT

In almost all copper mining companies, mine planning is done considering different time frames, leading to long-term (life-of-mine) (LOM), medium-term (first three years) and short-term (first year, monthly, weekly, and up to daily plans). Shorter term plans are usually associated with more abundant information, hence models with lower uncertainty. However, they capture more of the variability found on the geological attributes. In long-term models, usually estimation methods tend to hide this variability, providing smoothed interpretations.

Medium and long-term plans consider average values for the parameters and optimisation techniques are applied aimed at maximising the economic profit. Short-term plans, on the other hand, are made to comply with the medium-term promises, maximising the use of the available resources (equipment and processing capacities) and dealing with the variability not characterised in the previous planning stages. This generates an important gap between the short-term and the medium and long-term plans.

A case study was made using an important oxide copper mine, where the variability found in the short-term plan has a large impact in the productive process, thus reducing the daily ore grade variability is an important goal. In this paper, this planning issue is addressed by creating medium-term mine plans using mixed integer programming which are compared using the output of a simulation of the daily extraction that is aimed at satisfying the daily constraints of the processing plant, the availability of mining equipment and the variability of ore grade. The result shows the expected gap between these mine planning processes, which suggests correcting some of the parameters used in future medium and long-term plans.

INTRODUCTION

Mine planning in copper mines is commonly done in four stages, which are represented in Figure 1. Strategic planning includes the company's vision, looking for alternatives to create more value for the company (Whittle and Wharton, 1995; King, 1999; Epstein *et al*, 2003). Once an alternative is chosen, it is developed into the business plan, which considers the LOM, with information at the yearly level. The medium-term plan shows more detail in the first five years of production. The main scope is to ensure the conditions for fulfilling the business plan. The first year is described on a monthly basis, the second and third years are detailed up to a quarterly basis; finally the fourth and fifth years are described on a semester basis. The short-term plan is divided into four-day plans and daily plans, which are more detailed.

The medium-term plan considers monthly information for the first year to fulfill the first year of the long-term plan (Kostas, Pelley and Calder, 1987). A sequence of extraction and feasible cut-off grade strategy are generated to fulfill this plan. However, for the short-term plan, parameters

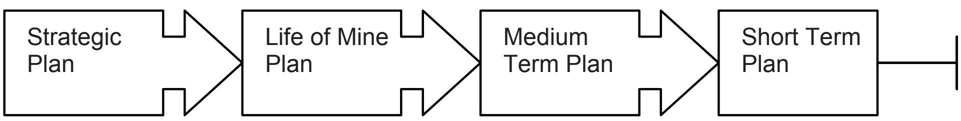

FIG 1 - Mine planning stages.

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that were simplified in the medium and long-term planning stages now become relevant and must be incorporated as new sources of uncertainty in the mining plan (Horsley, 2002). The addition of these new variables adds complexity to the decision-making process performed by the mine planner. Quantifying the variability of the mining process becomes necessary, since it is relevant for the processes of extracting, transporting and crushing the material. This leads to the generation of stocks, in order to add flexibility to the plan and ensure it can be accomplished.

Building and using stocks adds extra cost to the mining operation, however this cost may be necessary depending on the mining system studied. For instance, a mine where the ore is deposited in narrow structures, as is the case with mining copper oxides used in this study, may require more inventory management compared to more massive and uniform deposits. On the other hand, leaching and electrowinning require less variability in the processed ore grade, because the electrolytic process has a fixed current intensity.

METHODOLOGY

Medium-term mine plan

The medium-term mining plan in this case is made with 11 polygons. Each of these polygons may contain oxides, mixed, leachate, sulfides, or waste. The problem is solved using mixed integer programming and for this, the domain is divided into basic mining units (BMU) which set the discretisation of the problem. Then, the procedure is to estimate the reserves for each polygon according to the cutoffs presented in Table 1, thus forming the BMU for optimisation. Then each polygon will have 14 breaks of tonnage and grade, ie the problem of 11 polygons translates into 154 BMU. The problem has five destinations and three time periods, therefore the numbers of variables considered in the problem is 2310 with around 900 constraints, in addition to the variables associated with the handling of stock per period.

TABLE 1

Cut-off grade by material type.

Rock type	Cut-off grade [% CuT]			
Copper oxides	0.00	0.10	0.20	0.30
Oxide + sulfides	0.00	0.10	0.20	-
Leached	0.00	0.15	-	-
Sulfides	0.00	0.10	0.20	0.30
Waste	0.00	-	-	-

The maximum phase rate is 155 000 t/d and the stock rate is 45 000 t/d, the ore crusher requires a supply of 157 000 t/d. Figures 2, 3 and 4 show the spatial distribution of medium-term polygons.

The optimisation problem is solved to maximise the benefit function, giving the plan shown in Table 2.

TABLE 2

Medium-term plan.

Month	Ore to crusher										Oxide dump			Sulfide plant		Stock			Waste		Total
	From pit			From stock			Total														
	kt	Total Cu	Total Sol Cu	kt	Total Cu	Sol Cu	kt	Total Cu	Sol Cu	Kt/d	kt	Total Cu	Sol Cu	kt	Total Cu	kt	Total Cu	Sol Cu	kt	Total Cu	kt
1	3.851	0.62	0.50	859	0.45	0.36	4.710	0.59	0.48	157	765	0.36	0.27	**20**	0.56	0	0.00	0.00	**14**	0.12	**5.509**
2	4.087	0.65	0.54	623	0.45	0.36	4.710	0.62	0.51	157	527	0.36	0.27	**23**	0.56	0	0.00	0.00	**13**	0.12	**5.273**
3	3.977	0.66	0.53	733	0.45	0.36	4.710	0.63	0.51	157	625	0.36	0.25	**33**	0.56	0	0.00	0.00	**15**	0.12	**5.383**
Total	**11.914**	0.64	0.53	**2.216**	0.45	0.36	**14.130**	0.61	0.50	157	1.917	0.36	0.26	**76**	0.56	0	0.00	0.00	**43**	0.12	**16.166**

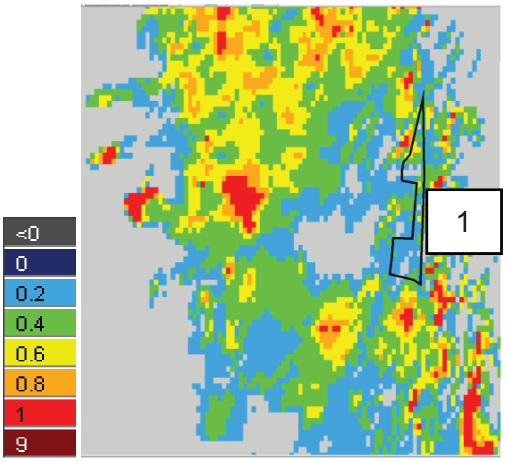

FIG 2 - Bench 2810.

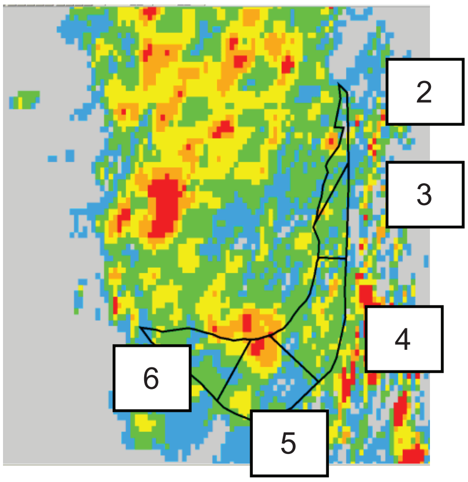

FIG 3 - Bench 2795.

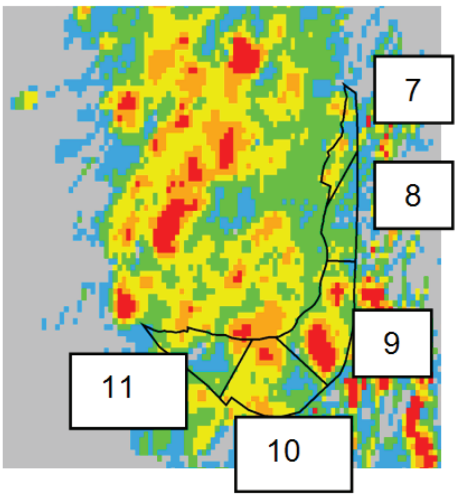

FIG 4 - Bench 2780.

Short-term mine plan

In this planning stage operational uncertainty is incorporated. The productivity used for the equipment is calculated based on the one year old data base. In this work variables that have a coefficient of variation greater than 0.1 are modelled as random variables. The coefficient of variation is defined as the ratio of standard deviation and the mean of a variable.

The variables considered are:

- Daily production of 73 yd³ shovels, which have an average of 70.51 kt/d with a coefficient of variation of 0.53. This distribution is modelled as a translated Weibull distribution with parameters $\alpha = 170.99$, $\beta = 4.86$ and $\gamma = -86.10$.
- Daily production of 56 yd³ shovels, which have an average of 56.52 kt/d with a coefficient of variation of 0.55. This distribution is modelled as a translated Weibull distribution with parameters $\alpha = 165.45$, $\beta = 5.89$ and $\gamma = -96.60$.
- Daily production of Front End Loader (FEL), which have an average of 18.93 kt/d and a coefficient of variation of 0.64. This distribution is modelled as a normal distribution with parameters $\mu = 18.92$, $\sigma = 12.09$.
- Daily production of ore crusher, which has an average production of 157.87 kt/d and a coefficient of variation of 0.33. Its production is modelled with a translated Weibull distribution with parameter $\alpha = 227.70$, $\beta = 5.53$ and $\gamma = -48.17$.

Block model dilution and extraction algorithm

The extraction of each polygon follows a sequential pattern to emulate the real movement of the shovel in operation, Figure 5. The methodology proposed considers that 1 - 5 blocks are extracted in a shift, the predominant geologic unit is considered and the grade of the extracted blocks is calculated by a weighted average.

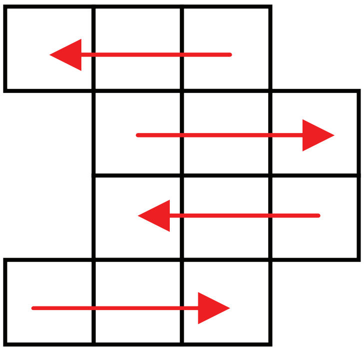

FIG 5 - Extraction sequence diagram.

Ore flow modelling

In each shift the mine planner must decide how much material from each production phase must go to crusher, high-grade stock, low-grade stock, and waste dump. To satisfy all the objectives and constraints that require the processing plant, and to handle the variability of shovels and crusher, the best blending strategy must be defined. In theory this problem can be modelled as a network flow problem, as shown in Figure 6.

The model considers three simultaneous ore phases: a low-grade stock, high grade stock and crushing.

The productivity for loaders, shovels and the ore crusher were considered as random variables. Eleven flow variables to be solved are detailed below:

x_{1t} Material flow from production phase 1 to ore crusher in t
x_{2t} Material flow from production phase 2 to ore crusher in t
x_{3t} Material flow from production phase 3 to ore crusher in t
x_{4t} Material flow from production phase 1 to high grade stock in t
x_{5t} Material flow from production phase 2 to high grade stock in t
x_{6t} Material flow from production phase 3 to high grade stock in t
x_{7t} Material flow from production phase 1 to low grade stock in t
x_{8t} Material flow from production phase 2 to low grade stock in t
x_{9t} Material flow from production phase 3 to low grade stock in t
x_{10t} Material flow from high grade stock to crusher in t
x_{11t} Material flow from low grade stock to crusher in t

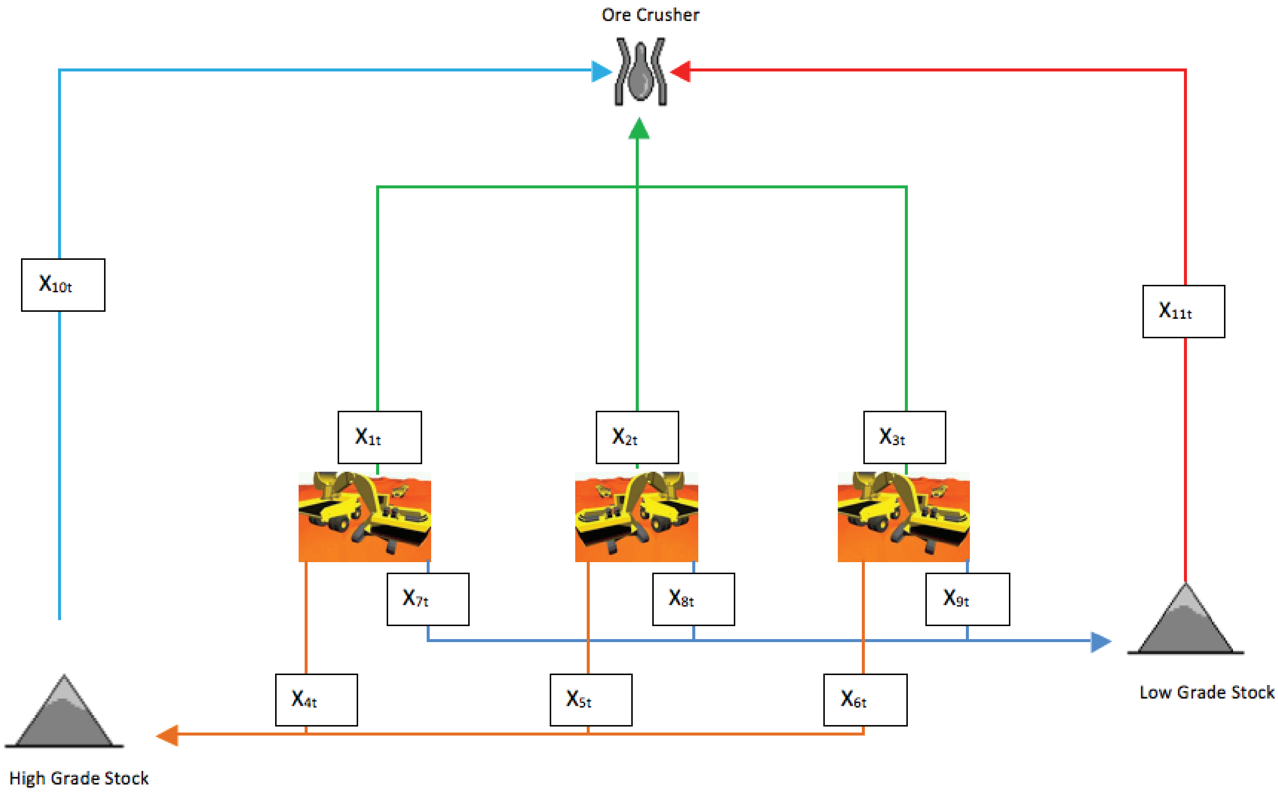

FIG 6 - Network flow problem.

The model parameters are:

$HGSt^{ini}_t$	high grade stock tonnage in t
$LGSt^{ini}_t$	low grade stock tonnage in t
Cr_t	ore crusher capacity in t
P_1	production capacity of phase 1 in t
P_2	production capacity of phase 2 in t
P_3	production capacity of phase 3 in t
c_1	haulage cost
c_2	load plus haulage cost
rhdl	maximum rehandle
δ	tolerance
$G_{St.CO}$	low grade stock cut-off
G_{tar}	target grade
G_j	grade for each material x_{jt}, with $j \in \{1,2...11\}$

The short-term plan mathematical model is:

$$\min: \sum_{i=1}^{9} x_{it} \cdot c_1 + \sum_{i=9}^{11} x_{it} \cdot c_2$$

Subject to:

$$x_{1t} + x_{4t} + x_{7t} = P_{1t} \qquad (1)$$

$$x_{2t} + x_{5t} + x_{8t} = P_{2t} \qquad (2)$$

$$x_{3t} + x_{6t} + x_{9t} = P_{3t} \qquad (3)$$

$$x_{4t} + x_{5t} + x_{6t} + x_{7t} + x_{8t} + x_{9t} + x_{10t} + x_{11t} \leq rhdl \tag{4}$$

$$x_{10t} \leq HGSt_t^{ini} \tag{5}$$

$$x_{11t} \leq LGSt_t^{ini} \tag{6}$$

$$x_{1t} + x_{2t} + x_{3t} + x_{10t} + x_{11t} \leq Cr_t \cdot (1 + \delta) \tag{7}$$

$$x_{1t} + x_{2t} + x_{3t} + x_{10t} + x_{11t} \geq Cr_t \cdot (1 - \delta) \tag{8}$$

$$x_{1t} + G_{1t} + x_{2t} \cdot G_{2t} + x_{3t} \cdot G_{3t} + x_{10t} \cdot G_{10t} + x_{11t} \cdot G_{11t} \leq Cr_t \cdot G_{tar}(1 + \delta) \tag{9}$$

$$x_{1t} \cdot G_{1t} + x_{2t} \cdot G_{2t} + x_{3t} \cdot G_{3t} + x_{10t} \cdot G_{10t} + x_{11t} \cdot G_{11t} \geq Cr_t \cdot G_{tar}(1 - \delta) \tag{10}$$

$$x_{7t} \cdot G_{7t} + x_{8t} \cdot G_{8t} + x_{9t} \cdot G_{9t} \leq (x_{7t} + x_{8t} + x_{9t})G_{St.CO} \tag{11}$$

where Equations 1, 2 and 3 dictate that all material removed should have a destination. The restriction in Equation 4 indicates that flows at the stock should be less than the rehandled material. Equations 5 and 6 ensure that the material extracted from the stocks should be less than their initial states. Equations 7, 8, 9 and 10 set the tonnage and ore grade for the crushing feed. Finally, Equation 11 ensures that the ore grade going to the low grade stock is lower than a maximum grade imposed.

Since it is not always possible to satisfy all constraints, these can be relaxed in the linear programming problem.

Results

The compliance rate for short-term simulation was 96.62 per cent, and relaxation averaged 9.3 per cent in 3.38 per cent of the remaining cases, the rehandle averaged simulated by three months is 31.95 kt/d, compared with 12.31 kt/d estimated in the medium-term plan. Figure 7 shows the variation in tonnage and grade of crushing power for different shifts.

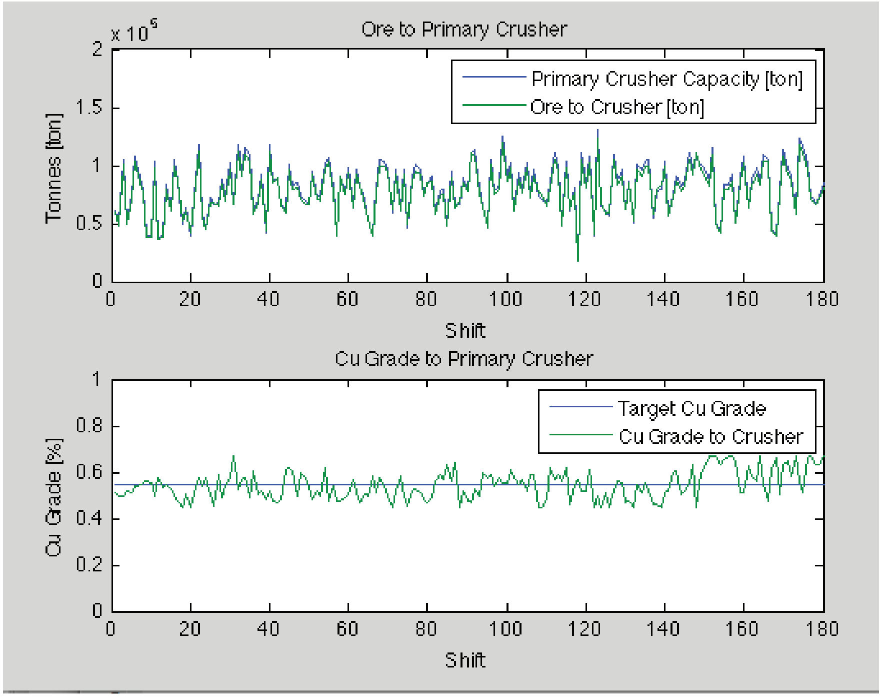

FIG 7 - Short-term plan.

CONCLUSIONS

Discrepancies between the middle-term and short-term plans may significantly reduce the economic benefit of a mining project. Quantifying the gap between these two models and optimising the short-term plan to comply as closely as possible to the middle term plan is usually very relevant. We proposed and illustrated a methodology based on Mixed Integer Programming to solve the short-term flow problem, in order to obtain the flows between production points and destinations that maximise the benefit accounting for the constraints as closely as possible.

The new methodology proposed allows the quantification of rehandled materials based on the ore distribution and the mining plan. In this case the difference between the estimated monthly rehandled tonnage from medium-term and the short-term plan is 19.63 kt/d. Since solving this problem is demanding in terms of the set up time of the optimisation problem, we recommend implementing this approach only for one critical period of the mine plan and then consider the rehandled material in the medium-term plans as a reference value, to accurately estimate the performance and cost of mining equipment.

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