Mine planning optimisation models to reduce diesel consumption of transport and arsenic emissions

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ABSTRACT

Nowadays in the mining industry, there is a growing concern for reducing CO_2 emissions and for work related to the concept of energy efficiency, in order to meet the high environmental standards imposed worldwide.

In mine planning there is awareness about the benefits that could be obtained if those environmental issues would be considered in the production plan; and that is the motive to design and develop, based on preliminary work, a new model of mine planning to reduce energy use, transportation costs and improve environmental aspects.

The reduction in transportation costs is achieved by controlling the material re-handling and pollutant emission (arsenic in this case); both are imposed as constraints to the material sent to the processing plant.

This paper presents a mathematical model that maximises the ore production under blending and complex geometrical constraints by optimising the mining and processing sequences in an open-pit mine, while reducing transportation costs and pollutant emissions. This work presents the results obtained by applying the model to two real case studies. Both show a different extraction sequencing from the traditional mine planning. The first case study increases the copper production by 22% and decreases with 92% the material re-handling, and the second case study pushed the arsenic limit per period back from 200 to 65 ppm.

The promising and interesting results indicate that a significant reduction in transport operations would effectively reduce energy consumption (diesel) and the associated costs, and the CO_2 and particulate material emission associated with transport; and also indicates that it is possible to have an arsenic emission control that improves the environmental aspects without compromising production levels of the mine.

INTRODUCTION

In open pit mines operation, approximately 20% of the total costs correspond to the material transportation [1], equivalent in energy terms to 31% of the total energy consumed for copper extraction [2]; these values are important to consider during project evaluation stage given that energy consumption is directly related to CO_2 emissions. During the pyrometallurgical processing of copper concentrates, arsenic emissions are also an important environmental issue and arsenic concentration should be controlled and maintained as low as possible in the copper concentrates. Previous studies have shown that about 41% of the arsenic entering the plant is released as gas and dust in the smelting and conversion stage [3].Arsenic content of the extracted ore is then an important parameter that should be taken into account in the mine planning.

These high costs of energy and the resulting polluting atmospheric emissions are the motivation to develop a new method of mine planning to reduce energy use, transportation fuel consumption and to improve environmental quality, reducing the associated CO_2 emission and the arsenic emissions in the plant.

A new mathematical method, that includes environmental and energetic variables into production planning and scheduling, has been developed and the impact of these environmental variable on the business value and on the extraction sequence has been evaluated.

The model is applying in two real case studies to obtain real values. The first one (case study A) shows how re-handling can be controlled to decrease the mileage travelled by trucks and the second one (case study B) shows how blending constraints can be used to limit arsenic content in the feed material by period, helping to control de arsenic emissions in the processing plant.

METHODOLOGY

This work presents some mathematical mine planning models developed to reduce transportation costs through a decrease of the material re-handling; and to improve the environment and concentrate quality through an arsenic control of the ore characteristics.

The original model BOS2 (Blending Optimisation Sequencing & Scheduling) is a mathematical model developed with integer programming as part of the Delphos Laboratory research activities. The model maximises the copper production computing an extraction sequence that considers the available stock subject to blending, geometric and capacity constraints.

The difference between the original BOS2 model and the one proposed in this paper are the precedence constraints. The original BOS2 uses the ring concept to restrict the access by period to a block group to be mined [4] while the new model sets ramp access per bench and establishes a minimum distance path to access to other blocks [5]. The ring concept indicates that the sequencing advance on the horizontal direction is made by setting an advance ratio per period; the disadvantage is that the concept imposes preferential directions, hindering horizontal progress in deep, discarding solutions that can lead to a higher value of the objective function [5].

Using some attributes from BOS2 and modifying the objective function (OP), the model can be used to control the material re-handling [5] and future arsenic emissions.

This work adapts the existing model considering two main variables:

- Environmental: Truck mileage (CO2 emissions) and arsenic content in ore (arsenic emission in plant).
- Energetic: Diesel consumptions by trucks.

Finally, this new model is applied to a real open pit mine and delivers a production programme that includes these variables**.**

Implementation and optimisation of this model was done using Python 2.6 and Gurobi 3.0.2 respectively.

CASE STUDY

The methodology was implemented in two real mines in a three months period, to evaluate different objectives in each one:

- Case study A is used to evaluate the truck energy saving by controlling material re-handling, using the original BOS2 model.
- Case study B is used to evaluate the decrease of the arsenic emissions on the processing plant by controlling the arsenic content in the ore. This case study uses the modified model presented in this paper.

Case study A

This mine process two types of ore (sulphide and oxide) and manages a stockpile for each ore type. The block model represents seven periods that process 700,000 tonnes in the first six periods and 50,000 tonnes in the last one. This case will be used to reduce the truck mileage between mine, stock and process plant to reduce the fuel consumption and CO_2 emissions.

The block model has 9,976 blocks measuring 10 x 10 x 15 m and corresponding to seven benches. From that total, 1,497 blocks contain sulphide ore with an average copper grade of 2.13% and 953 blocks correspond to oxide ore with an average copper grade of 1.09%.

This mine has a sulphide stock corresponding to 438 blocks with 1.06% copper grade and an oxide stock corresponding to 2,300 blocks with 1.03% copper grade.

Case study B

This case is used to evaluate the arsenic constraints and reduce the atmospheric emissions. The block model used corresponds to twelve periods distributed on three benches. This mine only process sulphides and the plant capacity is expressed in terms of hour-availability per period.

The block model corresponds to 3,482 blocks measuring 12.2 x 12.5 x 15 m and the average copper grade is 1.08%. In this case there is also a sulphide stock corresponding to 853 blocks and with 1.5% copper grade.

This company sets the arsenic limit per period in the feed material to 200 ppm, therefore this value must not be exceeded. The arsenic average content is 73 ppm for the entire block model and the maximum value in a block is 435 ppm.

MATHEMATICAL MODEL

As mentioned before, use integer programming was used for modelling and optimising the mine scheduling sequence. In this section, the variables and constraints considered by the model are introduced.

Each block is identified; for a set of blocks B, with its coordinates $r = (r_x, r_y, r_z)$ and a set of attributes A, in this case copper grade and arsenic content. For example: each block has attributes $Cu(r)$ for $r \in B, Cu \in A$.

Time periods are noted as $t = 1,2,\dots,T$, with T being the time horizon.

A set of pre-existing stock S is also added, corresponding to material available for processing but mined at some point before time-period 1. These are named the *static stocks* as opposed to the dynamic stocks described later. Each static stock is considered as a block in the sense that it has the same attributes (hence $Cu(s)$ is well-defined for each $s \in S$), but the attributes are normalised by tonnage (of stock) and has also a maximum tonnage $P(s)$.

The model decides which blocks are going to be mined or not and when; it also defines when each mined block is going to be processed. Similarly, it decides the tonnage to be processed from each stock. This means that, some blocks may be processed at a period $t>t'$, where t' is the period in which the block was mined. These blocks constitute what is called the *dynamic stock*. The decision of whether a block is processed immediately or goes to the dynamic stock is taken by the model in such a way that the goal function is maximised overall the time periods. Table 1 summarises the notation used in the paper.

Table 1 Main symbols used in the text

Symbol	Meaning	Symbol	Meaning
SP	Sulphide	OP	Ore production
OX	Oxide	m_{rt}	1 if block r mined by period t.
WST	Waste	p_{rt}	1 if block r processed by period t.
As	Arsenic	p_{st}	Processed tonnes from stock at t period.
Cu	Copper	*dest*	Block destination (OX, SP, WST.)

Variables

The model considers three sets of variables; mining and processing for each block and stock processing:

$$m_{rt} = \begin{cases} 1 & block\ r\ is\ mined\ in\ 1 \dots t \\ 0 & otherwise \end{cases}$$

$$p_{rt} = \begin{cases} 1 & block\ r\ is\ processed\ in\ 1 \dots t \\ 0 & otherwise \end{cases}$$

$$p_{st} = tonnage\ extracted\ from\ stock\ s\ at\ time\ period\ t.$$

To simplify the notation, the auxiliary variables are also introduced: $\Delta p_{rt} = p_{rt} - p_{r,t-1}$ and $\Delta m_{rt} = m_{rt} - m_{r,t-1}$ when t>1, and $\Delta p_{r1} = p_{r1}$, $\Delta m_{r1} = m_{r1}$ if t=1

Objective function

For each block an ore grade *Ore(r)* is considered. The idea is to maximise the total copper ore production over the T time-periods, Equation (1). As in this there are two mines with different characteristics, the objective function (OP) is also different because one processes oxides and sulphides, while the other only processes sulphides. For this equation *des(r)* is defined as the final block destination (OX, SP, WST, see Table 1 for descriptions); and *Ore(r)* as the block mineral content (which is assumed equal to zero for the waste blocks, *i.e.*, when *dest(r)* =WST).

$$\text{OP:} \sum_{r \in B} \sum_{\mathrm{t}=1}^{\mathrm{T}} Ore(r) \Delta p_{rt} \tag{1}$$

Structural constraints

This indicates that blocks can be mined and processed only once and that only mined blocks can be processed. Limited stock is assumed.

$$m_{r,t} \leq m_{r,t+1}, \quad p_{r,t} \leq p_{r,t+1} \qquad (\forall\ r \in B)(\forall\ t = 1 \dots T) \tag{2}$$

$$\sum_{t=1}^{T} p_{st} \leq P(s)(\forall\ s\ \in S) \tag{3}$$

Mine and processing capacity constraints

The mine capacity is controlled by the equipment used in both case studies, and that determines the *tonnes* that can be mined per period. However the processing capacities are different in each case. Case study A, has the plant capacity set by tonnes per period while case study B is set by availability plant hours per period. Because of that difference it is necessary to establish two processing capacity equations.

For each attribute $tonnes \in A$ and time-period t there is a lower bound $M^{-}(tonnes, t)$ and an upper bound $M^{+}(tonnes, t)$ that limit the overall $tonnes$ mined for the corresponding time-period, Equation (4) and similarly, for case study A, a lower and upper bounds $P^{-}(tonnes, t), P^{+}(tonnes, t)$ for the overall processed $tonnes$ for that time-period (5). For case study B, each attribute $hour \in A$ and time-period t there is a lower and upper bounds $P^{-}(hour, t), P^{+}(hour, t)$ for the overall processed $hour$ at that time-period, Equation (6).

The lower bound may be $-\infty$ and similarly the upper bounds to be $+\infty$ if the constraint does not apply for the attribute.

$$M^{-}(tonnes, t) \leq \sum_{r \in B} tonnes(r)\ \Delta m_{rt} + \sum_{s \in S} p_{st} \leq M^{+}(tonnes, t) \qquad (\forall\ t \in T) \tag{4}$$

$$P^{-}(tonnes,t) \leq \sum_{r:dest(r)\neq \mathrm{WST}} tonnes(r)\,\Delta p_{rt} + \sum_{s} tonnes(s)p_{st} \leq P^{+}(tonnes,t) \quad (\forall\, t \in T) \tag{5}$$

$$P^{-}(hour,t) \leq \sum_{r:dest(r)\neq \mathrm{WST}} hour(r)\;\Delta p_{rt} + \sum_{s} hour(s)p_{st} \leq P^{+}(hour,t) \qquad (\forall\, t \in T) \tag{6}$$

Blending constraints

The proposed model considers average processing constraints, which are weighted by a certain attribute. For time-period t and $tonnes, As \in A$ there is a lower bound $P^{-}(tonnes, As, t)$ that limits the average $tonnes$ (weigthed by As) to be processed for that time-period and similarly $P^{+}(tonnes, As, t)$as an upper bound on the average $tonnes$ (weigthed by As) to be processed for that time-period.

The constraint corresponds to a linearisation of:

$$P^{-}(tonnes,As,t) \leq \frac{\sum_{r:dest(r)\neq \mathrm{WST}} tonnes(r)As(r)\Delta p_{rt} \;+\; \sum_{s} As(s)p_{st}}{\sum_{r:dest(r)\neq \mathrm{WST}} tonnes(r)\Delta p_{rt} \;+\; \sum_{s} p_{st}} \leq P^{+}(tonnes,As,t)\;(\forall\, t = 1 \ldots T) \tag{7}$$

Precedence constraints

The slope precedence is modelled using a di-graph $S = (B, A_S)$, where $(p, s) \in A_S$ if block p (predecessor) must be extracted before block s (successor)as shown in Figure 1. The constraint is:

$$\mathrm{m_{s,t}} \leq \mathrm{m_{p,t}} \;\; (\forall\,(\mathrm{p,s}) \in \mathrm{A_S})(\forall \mathrm{t} = 1 \ldots \mathrm{T}) \tag{8}$$

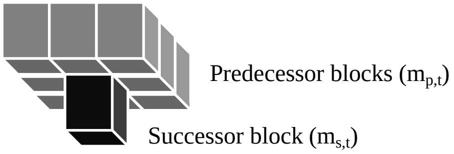

Figure 1 Precedence rules based on slope constraints.
The extraction of predecessor blocks must be first to get to successor block

We also have a neighbouring graph $N = (B, E_N)$, where $\{u, v\} \in E_N$ if block u is a neighbour of block v. This neighbouring relation is converted into a precedence relation by considering a set of *access points* (*ramps*) $\Lambda \subset B$ and a length $\ell(u, v)$ for edge $\{u, v\}$, so it calculates the shortest path from each $u \in \Lambda$ to each block $r \in B$ obtaining a partition of B into direct trees whose roots are the ramps. Assuming each block is reachable, this produces a second precedence relation in which each block (but the ramps) has one predecessor (apart from those considered in the slope precedence), which can be coded as direct tree $H = (B, A_H)$ where $(p, s) \in A_H \Rightarrow \{p, s\} \in E_N$. As expected the final constraint reads:

$$m_{s,t} \leq m_{p,t} \; \forall \; (p, s) \in A_H. \tag{9}$$

Stock constraints

We consider a number of constraints related specifically to the stocks. Two types of stocks are distinguish in this case: static stock (given by the initial stock in the model), and dynamic stock (created by the model, delaying the processing of a block to a period after the one it was mined).

Dynamic stock limit

This constraint limits the growth of dynamic stock by bounding the fraction of blocks whose processing time is delayed to further periods. We consider a saturation factor $F(tonnes, t)$ for attribute $tonnes$ and time-period t.

$$\sum_{r:dest(r)\neq \mathrm{WST}} tonnes(r)\, p_{rt} \;\geq\; F(tonnes, t) \sum_{r:dest(r)\neq \mathrm{WST}} tonnes(r)\, m_{rt} \qquad (\forall\, t \in T) \tag{10}$$

Notice that this constraint is applied on the original variables; therefore it accumulates for processed and mined blocks up to time-period t.

RESULTS

The results are presented in two parts. The first one presents the results obtained in the evaluations of different mine planning methods to reduce material re-handling (case study A). The second part presents the result of a reduction of the arsenic limit permit (case study B).

Re-handling

The results obtained from the evaluations of different scenarios for the study case A are presented in Table 2.

Table 2A Basic descriptions of the scenarios evaluated to achieve a re-handling material to decrease without compromising copper production.

Scenario	Description
Base Case	Made by the mine planning expert without model assistance.
Best Case	Obtained using the original BOS2 model. It is not operative.
Operative Case	Made by the mine planning expert using BOS2 results (*Best Case*) as a guide.
New Model	Obtained using the model proposed in this paper. It is not 100% operative.

The first result is named *Base Case*. It corresponds to an operational extraction sequence constructed by the mine planner without using the model proposed in this paper. In particular, the manual process used by the planner is not optimised.

The second result is using model assistance. From these evaluations, the *Best Case;* which delivers the maximum copper production was obtained, but this is not an operative option. These original model results were used because this scenario has an operative plan, and it is therefore easier to compare the effect of making it operational.

Then the *Operative Case* constructed by the planner, uses the *Best Case* results as a guide and makes it an operative production plan. The problem is that when the *Best Case* goes to *Operative Case* there is a loss in the copper production. However, these results are still always better than the ones obtained in the *Base Case.*

In the *New Model,* once a block is removed, there is a limited number of periods to extract the next block in the horizontal precedence arc and it has also better geometric connectivity and saturates also the transport capacity [5]. However, the obtained result is not 100% operative.

As shown in Table 3, the final results are as expected. By traditional planning *(Base Case),* the lower copper production and the higher material re-handling is obtained. The use of the model *(Best Case)* delivers the highest copper production and re-handling, so when the planner is involved in the scheduling plan (*Operative Case*), it reduces the final copper production and re-handling. However, these are better results than those obtained in the *Base Case.* By implementing the *New Model*, a higher copper production than in the *Operative Case* and less re-handling is obtained, than in the other cases. The advantage of this *New Model* is that it considers more geometric constraints which allows for going to an operative plan without a significant loss in the copper production. These values are presented graphically in Figures 2 and 3.

Table 1 Results from the evaluation of the case study using different methodologies.

	Base Case	Best Case	Operative Case	New Model
Re-handling (ton)	428,024	366,997	93,512	32,325
Cu Production (ton)	87,779	114,143	99,877	107,179

The table presents the results of the material that are sent to the plant from stock (re-handling) and the final copper production.

Comparing this *New Model* to the *Base Case*, there is a 22% increase in copper production and a 92% decrease of the use of stock. These encouraging results were obtained because the model calculates the extraction sequence in all time horizon (as opposed to the planner, which makes it period by period), this allows satisfying the blending (mixing) conditions without resorting so much to stock.

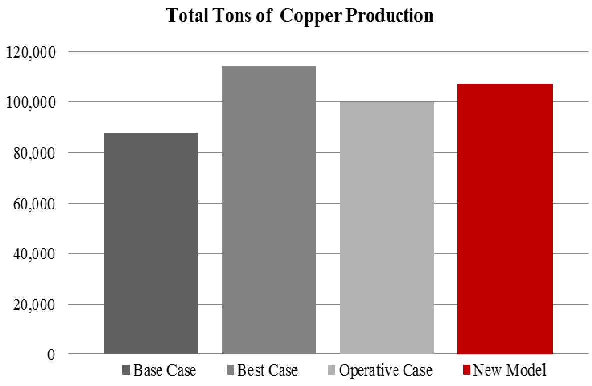

Figure 1 Total copper production (tonnes),for case study A, delivered by using different mine planning methods

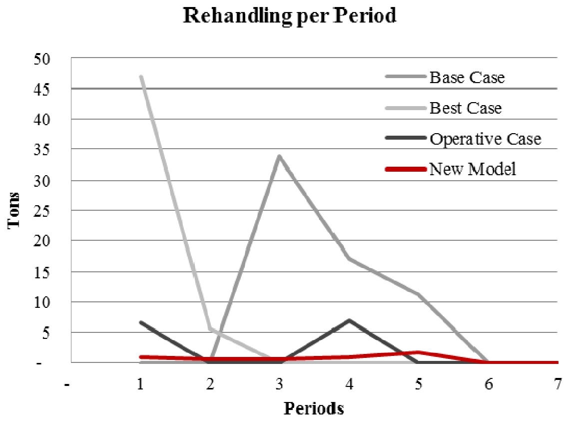

Figure 2 Re-handling material per period using diferent methodologies. The *New Model* shows a homogeneous behaviour in terms of the amount of re-handling material that is processed in each period

When the planner makes the transition from *Best Case* to an *Operative Case*, total copper production is reduced by 12%, therefore if this loss is extrapolated to the *New Model* (not operative), a total copper production of 94,318 tonnes is expected . This production is still better than the one obtained in the *Base Case*.

Arsenic control

The arsenic control is done using the same *New Model* method, but in this case arsenic blending constraints are added, (Equation 7), always looking for the best plan which delivers the higher ore production (Equation 1) without compromising environmental quality. In this case the company sets the maximum permit limit on 200 ppm of arsenic and as shown in Figure 4 this block model (Case Study B) has some blocks (1%) with arsenic content over the 200 ppm limit, but the arsenic content of most of the blocks is below this value. However, it is important to control the mine and process scheduling because these high values can exceed the limit for some periods.

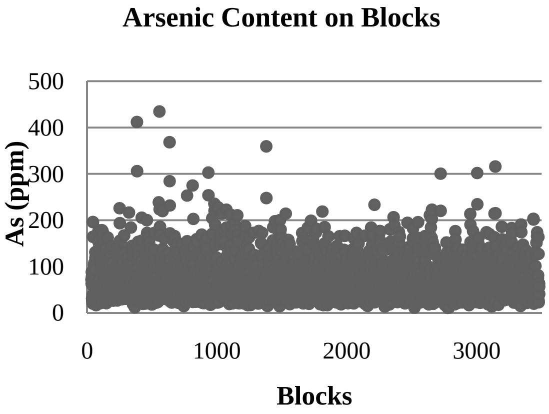

Figure 4 Arsenic content from Case Study B block model. The graph shows that most data are below the 200 ppm limit set by the company

At first, the block model is evaluated with a 200 ppm constraint of average arsenic content in the ore processed per period, but to evaluate the model with two more limits, the arsenic average and standard deviation must be added and subtracted from the block model (Table 4).

Table 4 Arsenic value statistics from Case Study B block model

Maximum	435 ppm	Standard Deviation	43 ppm
Minimum	11 ppm	Average + Standard Deviation	116 ppm
Average	73 ppm	Average + Standard Deviation	30 ppm

The first two evaluations (arsenic limit at 200 ppm and 116 ppm) were easily fulfilled because the limit is over the arsenic average, but when the arsenic limit is reduced to 30 ppm the solution was unfeasible, meaning that it is impossible to meet this constraint and fulfil the capacity constraints. So the limit was gradually increased to confirm this conclusion and up to59 ppm the model was unfeasible and from 60 ppm to 64 ppm the computer ran out of memory and no solution was found. This is why only the results obtained from imposing a maximum arsenic content of 200 ppm, 116 ppm and 65 ppm are presented.

In all three evaluations, the arsenic constraint was fulfilled (Figure 5) and the copper production is almost maintained (with a reduction of only 0.7%) for 200 ppm As and of 9.3% for 116 ppm As, (Figure 6). In all cases the capacity constraints (plant and transport) are met.

Figure 7 shows the results obtained using this *New Model*. This model preserves the final open pit geometry but delivers a different extraction scheduling and the correct connectivity between blocks makes the model more reliable and in consequence when the mine planner uses it as a guide to make it 100% operative, there will not be many losses in the total ore production.

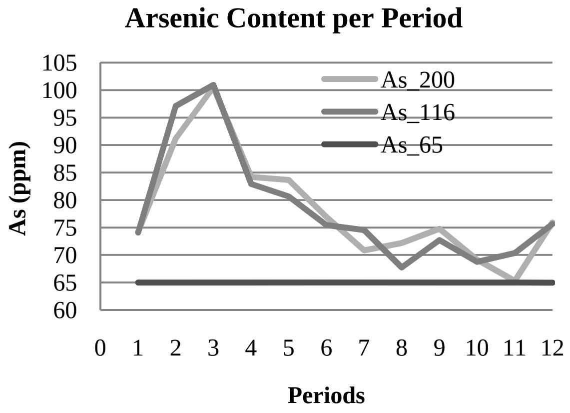

Figure 5 Arsenic content of the feed material to the plant per period once the *New Model* is used to do mine planning

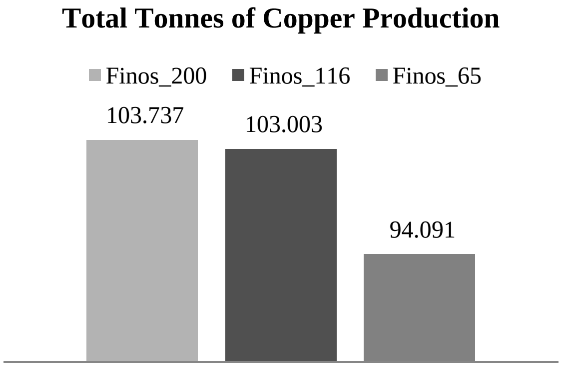

Figure 6 Total ore production in the three evaluations using the New Model and imposing different arsenic constraints

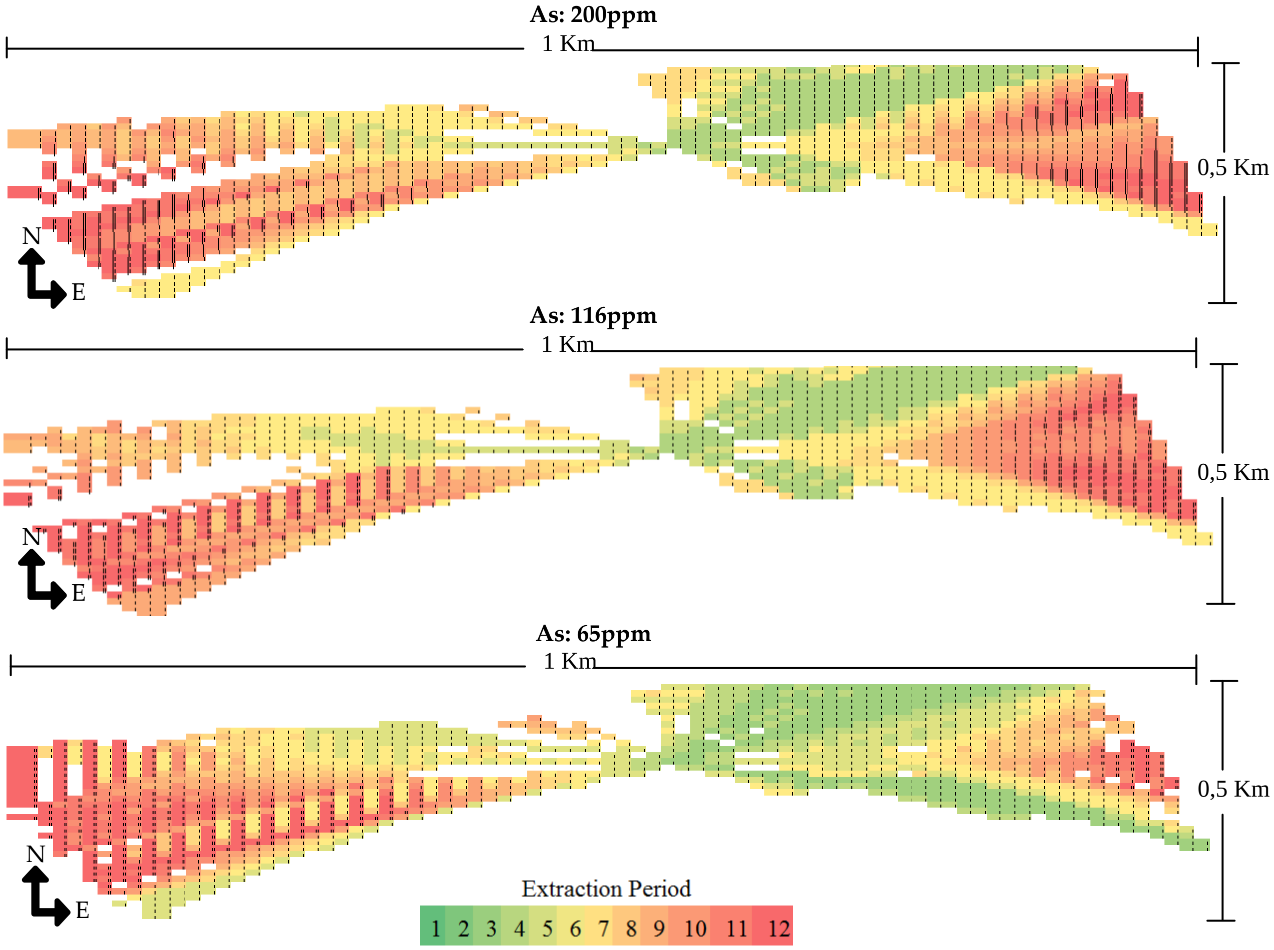

Figure 7 Geometry extraction from bench 3012 obtained with the New Model, for Case Study B, considering different limits for the arsenic content per period

CONCLUSIONS

This work develops, based on BOS2, a methodology for short-term mine planning that considers environmental variables associated with geological features of the rock. The mathematical model considers the optimal block extraction and processing sequences overall the time horizon and incorporates geometallurgical restrictions on the ore supply to the crushing plant, which has an impact on the cooper production, mine design and maintenance of the operation.

For the first case study the original BOS2 was adapted to a model that considers the distance travelled by trucks (re-handling) as an environmental variable because a significant reduction in transport operations would effectively reduce energy consumption (diesel), the associated costs and the CO_2 and particulate material emissions associated with transport.

To evaluate this parameter, four scenarios were compared: *Base Case, Best Case, Operative Case,* and *New Model.* Using the *New Model,* a 22% increase in the cooper production and a 92% decrease on re-handling were obtained.

This *New Model* was also used to evaluate the Study Case B in terms of controlling the arsenic atmospheric emission, controlling the arsenic content in the material processed in the plant. In this case, three scenarios were evaluated, each one with a different maximum limit of ore arsenic content per period.

With the arsenic constraint imposed by the company (200 ppm per period) the final copper production is 103,737 tonnes and when the arsenic limit is 116 ppm the ore production decreases only 1%; indicating that a significant decrease in arsenic emissions will not considerably affect the final mine production. In the third scenario, when the arsenic limit was 65 ppm, the copper production decreased 9% from the result obtained with the highest permit limit. These results show that if a mineral deposit presents a high arsenic content, it is possible to maintain a high ore production and to control the arsenic emissions to meet the environmental standards.

In both cases (re-handling and arsenic control) the final result delivers a different extraction sequence, keeping the same open-pit geometry, and ensures an environmental mining development.

This model could be also adapted to reduce energy consumption in other processes such as crushing and grinding because optimisation models allow considering mixtures constraints in material, which means greater efficiency in comminution equipments.

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