Short and Medium Term Mine Planning in Selective Underground Mining considering Equipment Performance

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Abstract— Generally, mine planning is undertaken towards the development of production plans using fixed parameters, which provide little flexibility towards changing production plans in case of unplanned events. Therefore, it is important to introduce variables during the planning process, which would allow the mine planning to have a better alignment with real mining conditions and would allow the decrease in the operational uncertainty towards the development of a more agile production plan.

The mine layout grows every day but it is very common that the equipment productivity is calculated with fixed parameters, which does not consider the size of the new developments and, thus, it does not consider the changing performance of the equipment, which will affect the mine production because of the associated changes in haulage time, variability in the equipment´s tasks and other influences resulting from the changing mine layout.

This paper evaluates influence of the changes in the equipment performances over a short- and medium-term mine plans on the mine production. The results show that the change in scheduling and sequencing of the activities and the new mine plan are more realistic when equipment performance is included in the evaluation in comparison with a scheduling that only considers resources constraints. The methodology was developed using tools currently available at the DELPHOS Mine Planning Laboratory, UDESS and DSIM, and by simulating the working scenario with varying performance of the equipment.

Keywords: mine planning, selective mining, equipment selection, UDESS, DSIM.

1. Introduction

The main objective of mine planning is the optimization of economic value for the different stakeholders. It is, therefore, natural for mine planners to model the production and the economic value of a project in terms of different parameters or decisions, which are then optimized to obtain the best possible economic value. The range of techniques that can be used is extensive and ranges from the manual evaluation of few scenarios to the utilization of advanced computational techniques, for example, mixed integer programming, to model the production of mine operations to arrive at the best-value plans.

The planning process requires various data, such as operational data that includes data related to the performance of the equipment. The equipment performance indicators are obtained from nominal equipment productivity parameters, which are adjusted using operational multipliers such as mechanical availability, operational losses, and others.

The planning process based on the static approach does not account for the variability of various mining tasks, the evolution of the layout over time, interactions between various pieces of equipment is complex to estimate. Indeed, the actual values of these parameters depend on the long-term plan; for instance, the transportation capacity of a mine depends on the relative transportation distances and, therefore, is not a constant parameter over the life of the mine.

Therefore, the drilled meters and productivity (*KPI's*) used in the long-term change over time (Figure 1) and the indexed values evolve depending on the mine size, due to travel times and events occurring during the life of the mine.

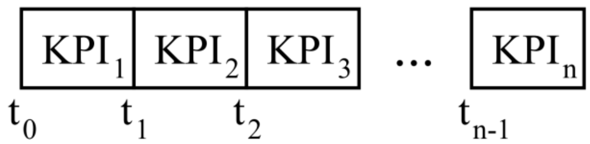

Figure 1. KPI's function of time

Therefore, planning process should follow an iterative approach (Figure 2) commencing from an initial plan that can be obtained from an optimization process and using simulations to estimate equipment productivity. The simulation results, new parameters, are then used as an input into the optimization process to update the plan accordingly [8].

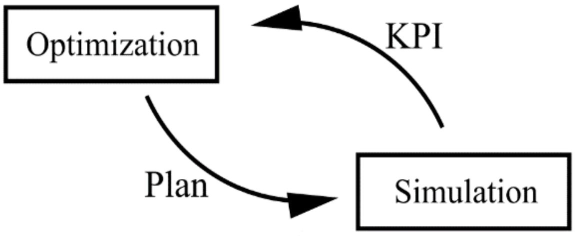

Figure 2- Iterative approach to Mine Planning: Optimization and Simulation

Unfortunately, implementing this methodology can be very difficult because optimization solvers, such as, Gurobi®[7], CPLEX®[2], and others, as well as simulation softwares (Arena®[1], ProModel®[12], etc.) are specialized to perform specific tasks and possess only limited capabilities to interact with other software in an efficient way. These limitations led to the development of the optimization and simulations models for mine planning that allow the integration between solvers and/or simulation softwares by means of scripting. The models (which are also available as software tools) are called UDESS and DSIM and are for optimization and simulation, respectively.

1.1. Optimization Model

The optimization model used is a general scheduling model that takes as inputs: (a) activities (or tasks), their lengths and operational resource requirements, (b) the logical precedencies for these activities, and (c) the net profit of performing such activities. The model computes the schedule of activities that complies with precedence and resource availability in such a manner as to maximize the economic value (or minimize cost). This model has been successfully tested in scheduling of production and preparation for panel caving in the deterministic scenarios [13], under operational uncertainty [10], and in scheduling of projects under price uncertainty [9]. It has also been used in an interactive way, as shown in Figure 2, but using other models; for example, material flow in a caving mine [4], seismic risk [3], and dilution in a cut and fill [11].

1.2. Simulation Model

Contrary to commercial solutions, the simulation model is specifically oriented to material handling in open pit mines as well as production and preparation in underground mining. It implements: (a) a set of functions that allow to easily define a layout and modelling of movement of equipment, (b) several agents (trucks, shovels, LHDs, etc.) that can be used as is or extended to model more complex situations, and (c) reports specially tailored to mine operations (cycle times, production)

To-date it has been mainly used in open pit mines, for example, to study the variability of production due to operational and geometallurgical uncertainty [5] or to simulate autonomous hauling systems [6].

2. Methodology

The methodology used in this research is summarized in the following steps:

1. Layout creation, which considers both preparation and extraction activities simultaneously.
2. Development of a production plan using an optimization model (UDESS), considering KPI inherent to the production equipment that is in operation.
3. Simulation of the production plan and material movement at certain time intervals using a simulator (DSIM).
4. Elaboration of a new production plan using the results of the simulation and the new KPI´s as inputs.
5. Analysis of the changes in the production plan, considering the new information obtained
6. Iteration from Step 3.

The mine layout used in the study (Figure 3) corresponds to a mine extracted by a bench-and-fill method, which considers two productive sectors, East and West, each with 5 levels, which must be prepared before commencing the operation. It should be noted that only drifts require to be developed in the simulation and that all the infrastructure required separately (mine entrance and inter-levels ramps, access drifts, ventilation, ore passes) are ready at the beginning of the simulation. Material handling from the ore passes out of the mine is not part of the research.

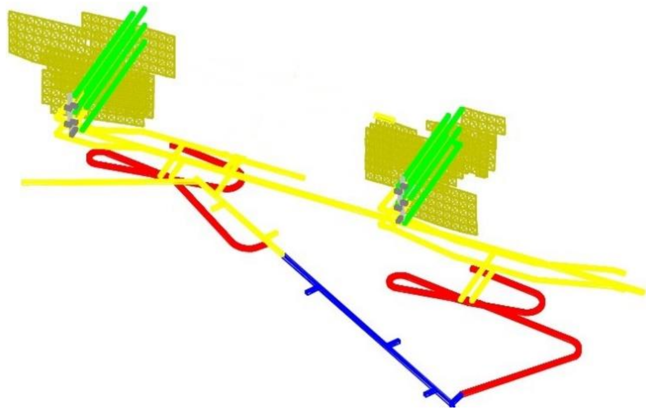

Figure 3- Mine layout used for the bench-and-fill method

For the simulation, it is further assumed that one day contains 3 operating shifts, a shift change of a duration of one hour and one hour for meal per shift.

In addition, the simulation environment considers:

- Program Delays: time intervals in which the equipment is not in operation because the operators are in a shift change or in meal time.
- Operational Losses: equipment waiting time because another equipment is traveling through the same drift
- Backup Time: interval in which the equipment is available to operate but there are no pending tasks for its operation

- Non-Available Time: interval in which the equipment is in the workshop, due to scheduled or unscheduled maintenance.
- Effective Time: time in which the equipment are performing an assigned task or the time of travel to their destination.

In development task, the activities carried out are drilling, explosive loading, blasting and ventilation, muck removal, hang-up removal, shotcreting and roof support.

In operation task, the activities carried out are drilling, loading of explosives, blasting and ventilation, ore extraction and stope filling. The filling is carried out after three exploitation processes.

The list of equipment used is shown in Table 1.

Table 1- Equipment quantity in layout

Type	N°	Type	N°
LHD	2	Jumbo	2
Scaler	1	Simba	2
Explosives	1	Boltec	1
Shotcrete	1	Backfill Truck	3

Since each of the simulations has variability, each of the possible scenarios can either fulfill the plan or not and, therefore, the simulations must be compared with the result of the optimization process.

There are two different models, mathematical and simulated, that must interact; indexes are proposed that compare the operability of the proposed production plan because the mathematical model only considers precedencies and resources that must be used but does not consider the operation of the system. The simulation provides several scenarios in which the production plan generated might be replicated, checking whether the production plan is fulfilled and whether each task individually, both development and extraction, may or may not be performed.

Assuming that an activity is the complete process referred to the development of a complete gallery or the extraction of all the stopes in an extraction gallery and an iteration is the generation of a plan between the process of optimization and simulation (Figure 2), the following parameters are defined:

- *i*: Activity. $i \in 1,...N$
- *j*: Replica. $j \in 1,...R$
- *h*: Iteration. $h \in 1,...L$
- B_{ih}= period in which *i* activity begins in the UDESS plan in *h* iteration.
- F_{ih}= period in which *i* activity finishes in the UDESS plan in *h* iteration.
- SB_{ijh}= period in which *i* activity begins in the *j* DSIM replica in h iteration.
- SF_{ijh}= period in which *i* activity finishes in the *j* DSIM replica in *h* iteration

Therefore, for

$$y_{ijh} = \begin{cases} 1 \; if \; SB_{ijh} \leq B_{ih} \\ \quad otherwise \end{cases} \tag{1}$$

$$z_{ijh} = \begin{cases} 1 \; if \; SF_{ijh} \leq F_{ih} \\ \quad otherwise \end{cases} \tag{2}$$

the following relationships can be written:

$$PB_h[\%] = \frac{\sum_{i=1}^{N} \sum_{i=1}^{R} y_{ijh}}{N * R} \tag{3}$$

$$PF_h[\%] = \frac{\sum_{i=1}^{N} \sum_{i=1}^{R} z_{ijh}}{N * R} \tag{4}$$

For the present research, the amount of development and extraction activities is defined as N = 95 and 35, respectively, while the number of replicas is R = 100 and the dilution is defined as:

$$Dilution[\%] = \frac{Waste}{Ore + Waste} \tag{5}$$

Dilution is considered as the amount of waste that enters to the material extraction. In the present case, using Equation 5, it is considered that the waste corresponds to 20% of the ore with dilution equal to 16.6%.

Optimization model is considered for the short-medium term of one year with periods of 1 month, while simulation model has a length of four months, where the values observed in the fourth month are used for the rest of the year.

3. Results and Discussion

As the iterative process was undertaken, it was observed that the productivity obtained did not change between the iterations in both cases, without and with dilution in Figure 4 and 5, respectively, resulting in the equipment hauling the same quantity of material, although there was an increase in the ore extraction each month. When considering dilution, daily production increased slightly.

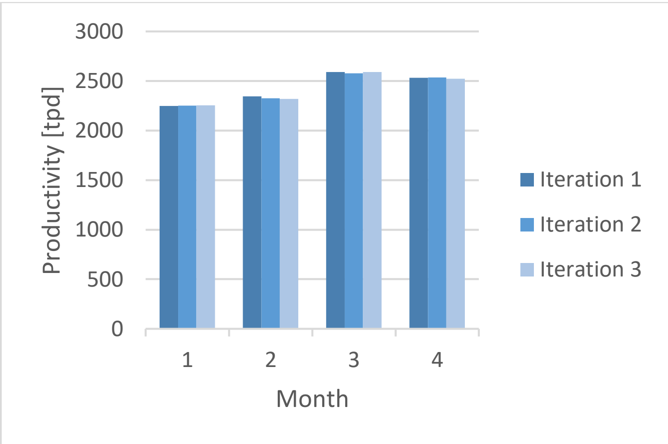

Figure 4 – Average Productivity in DSIM Plan without dilution

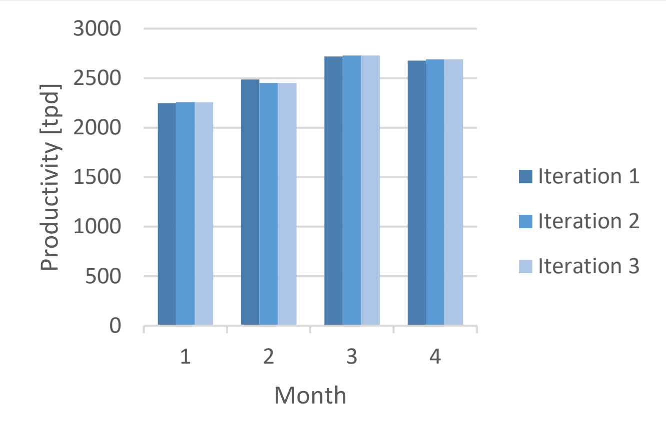

Figure 5 – Average productivity in DSIM Plan with dilution

The drilled meters using horizontal and radial drilling equipment were compared showing small variation between the iterations (Tables 2 and 3).

The amount of dilution does not depend on the drilled meters and thus it is expected that this variable remains the same in both cases, without and with dilution (Table 2 and 3).

Table 2- Horizontal Drilling Performance

		Month 1	Month 2	Month 3	Month 4
Without Dilution	Iteration 1	76,906	60,324	60,520	57,192
	Iteration 2	76,810	60,555	60,323	57,254
	Iteration 3	76,919	60,323	60,466	56,911
Dilution	Iteration 1	76,821	60,830	59,776	56,845
	Iteration 2	76,683	60,758	59,910	57,022
	Iteration 3	76,623	60,402	60,146	56,923

Table 3 – Radial Drilling Performance

		Month 1	Month 2	Month 3	Month 4
Without Dilution	Iteration 1	366	11,013	14,858	14,918
	Iteration 2	492	10,478	14,701	14,919
	Iteration 3	552	10,553	14,779	14,784
Dilution	Iteration 1	443	11,003	14,565	14,714
	Iteration 2	640	10,492	14,703	14,874
	Iteration 3	687	10,276	14,459	14,695

Table 4 indicates the resource constraints used in the optimization model, considering the average of horizontal and radial meters perforated according to the simulation model. The first period constraints are also obtained by using simulations, taking the maximum drilling value obtained, using an extraction schedule from the bottom up.

Table 4- Constraints in optimization model (UDESS)

Iteration	Drilling	Period	Upper Limit [m/month] Without Dil.	Upper Limit [m/month] Dilution
1	Horizontal	1-12	76,500	76,830
	Radial	1-12	15,000	14,660
2	Horizontal	1	76,900	76,820
		2	60,325	60,830
		3	60,520	59,780
		4-12	57,200	56,850
	Radial	1	370	445
		2	11,000	11,000
		3	14,900	14,565
		4-12	14,900	14,715
3	Horizontal	1	76,800	76,685
		2	60,550	60,760
		3	60,320	59,910
		4-12	57,250	57,025
	Radial	1	490	640
		2	10,480	10,500
		3	14,700	14,700
		4-12	14,920	14,875

Figures 6 and 7 show the mine plan obtained by the optimization model without and with dilution, respectively. In the first iteration, the result only considers the resources constraints and the preceding activities, with the operational parameters not considered as part of the input data. In both cases, the amount of material extracted is much higher for the first 3 months and then declines in the last periods, decreasing 30% and extracting irregular material amounts.

The case without dilution (Figure 6) shows that certain periods do not have material extraction; these periods correspond to the filling of the stopes only.

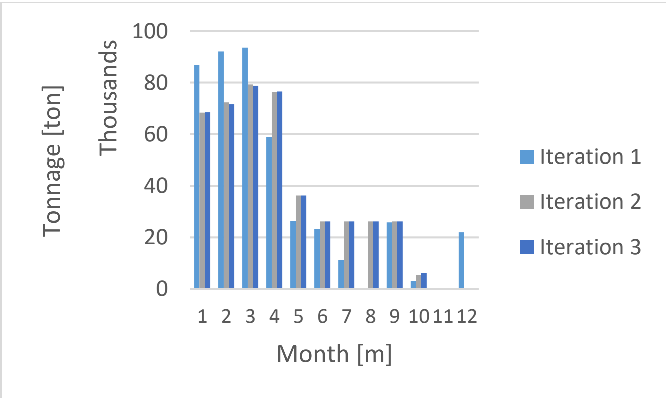

Figure 6 – UDESS Plan without dilution

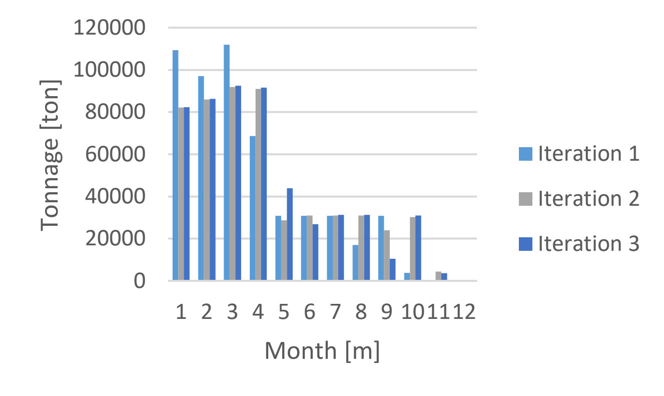

Figure 7- UDESS Plan with Dilution

Table 5- Optimization model NPV

Iteration	Objective Value [MUS$] Without Dil.	Objective Value [MUS$] Dilution
1	761.89	756.4
2	760.26	751.94
3	760.14	752.83

As shown in Table 5, the variation of the NPV is very small, decreasing slightly with each iteration. However, the plan delivered by the optimization model shows that the amount of material extracted on a monthly basis differs; it commences with no material extracted with a gradual decrease of extraction towards the end periods.

Table 6- Adherence Indexes in Development and Extraction Plan

	Iteration	1	2	3	1	2	3
		Without Dil.			Dilution		
Development	PI_h	91.4	92.8	93.1	88.5	91	92.7
	PB_h	56	66.5	66.9	54.7	66.2	66.4
Extraction	PI_h	56.8	90.7	91	62.6	93.1	91.2
	PB_h	43.3	78.2	81.1	51.3	78	78.8

When considering these adherence indexes the most apparent changes are shown in Table 6, indicating that the new plans tend to improve adherence to the assigned plan as compared to an original plan that does not necessarily consider the mine operation. The change in the index does not necessarily increase when performing more than one iteration. but if it considers that the new plans consider a major operative sequence.

4. Conclusions

The optimization model considers precedence and resource constraints in the activities performed and, from the point of view of NPV maximization, the optimum result is achieved, but it does not consider the system's operation. On the other hand, the application of the methodology presented in this paper allows to feed back the new information gathered from the simulations and to achieve an operative and optimal development and production plans.

It was observed that the changes in both the optimization and simulation models show remarkable improvements between the first and second iterations in the cases analyzed, achieving an improvement in the adherence index parameters of almost 35%, although in none of the cases this compliance rate exceeded 92%, which means that on average the plan is considered as overestimated in terms of available resources.

The production plans generated a remarkable change between first and second iteration made, but the result remains practically constant between the second and third iteration. However, for the second and third iteration, the scheduling of activities changed in some periods, which might have influenced the outcomes of the simulation. Therefore, it is recommended to undertake further studies on the influence of the variable scheduling on the stabilization and productivity indexes.

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