Optimal sequencing and scheduling for a block/panel cave mining

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ABSTRACT

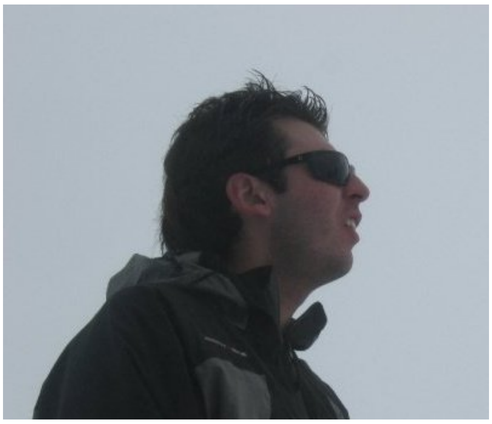
Currently, the mining industry creates the mine planning by using mathematical optimization. To achieve this, a mathematical model is proposed with an objective function such as to maximize the profit, to maximize the life of the mine, to minimize concentration of some pollutants, to minimize mining costs, to get a determinate confidence level or to get ore reserves. Also, certain constraints should be satisfied such as the production capacity rate or the plant production capacity rate. However, a loss of the economic value can be appreciated in large underground mining projects either by using a unique sequence of opening drawpoints (which is selected with a criteria, not necessarily related to the optimization) or by not considering the construction time of the underground mine infrastructure. It causes delays in the mine production with respect to the mine planning. Nowadays, in the mining industry these are common practices.

If these considerations were incorporated into the optimization process, the solution would be different. There would be another value for the objective function, and different opening drawpoint sequences.

This paper shows a novel, integrated way to make the mathematical optimization for underground mines. It considers the opening drawpoints sequence and drift development as a result of the optimization.

Finally, for production and development, the implementations of these models are respectively named BOS2Undergound and UDESS. These models were already presented in APCOM 2011. This paper corresponds to an actualization of that work.

BIOGRAPHY



Winston Rocher Anda, a mining engineer and masters student at the University of Chile, has participated in different activities and organizations during his studies, such as: scout group, student council for mining engineering, IIMCh, SME and recently IMMS, he has been a finalist in the National Math Olympiad, participate a study of the Large Magellanic Cloud for the European Southern Observatory and had been an assistant for several courses in the university. All this culminated in the award Juan Brüggen, for the best graduate of the mayor of mining engineering of the University of Chile in 2010. Winston is currently pursuing a Mining Masters in the same university where he completed his undergraduate degree, at Delphos Mine Planning Laboratory, working on underground development sequencing and scheduling; finalizing his second undergraduate degree as a Civil Engineer for a better understanding of solids and fluids; and, since April this year, working on the project Codelco Chuquicamata Underground.

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INTRODUCTION

Mine planning is the discipline of mining engineering that transforms a mineral resource into a mining business. The outcome of this process is the production plan that delineates the best strategy to make the mining business attractive. To achieve this purpose, mine planning incorporates the mathematical optimization as a power tool with a lot of constraints and an objective function that represents the strategy of the company or the client.

In particular, the underground mine planning is composed mainly of two components: production and infrastructure preparation or development. Often, the production exercise is performed into two decoupled stages: First, the mining exploitation unit sequence is determined (drawpoints or stopes as required). Second, planning the development of the infrastructure as required. Although each one is an optimal solution, to consider these two stages as independent processes does not necessarily conduce to find the optimal solution. The last case is a local optimum, but a global optimum is required. The last idea is as strange as imagining an open pit mine sequence without integrating the waste removal! This can bring new and troubling problems that have already been documented in the industry (Díaz and Morales, 2008).

In order to illustrate this decoupled process, Figure 1 shows six exploitation units with their respective values (net profit) connected with paths or required developments to reach from one exploitation unit to another. Each path has its cost to get to the next unit. Two different strategies have been proposed. The first one is to start from the best value unit and then select the best value unit between the neighboring connected values. The second strategy is to start from the path with the lowest cost, and select the neighboring paths with the lowest cost until finished. In the example, the implementation of both strategies results in different sequences or solutions with different net profits. However, both solutions that extract the same mineral should be considered to solve the problem. Therefore, with this simple example can be illustrated that this is not a trivial problem and deserves to be analyzed.

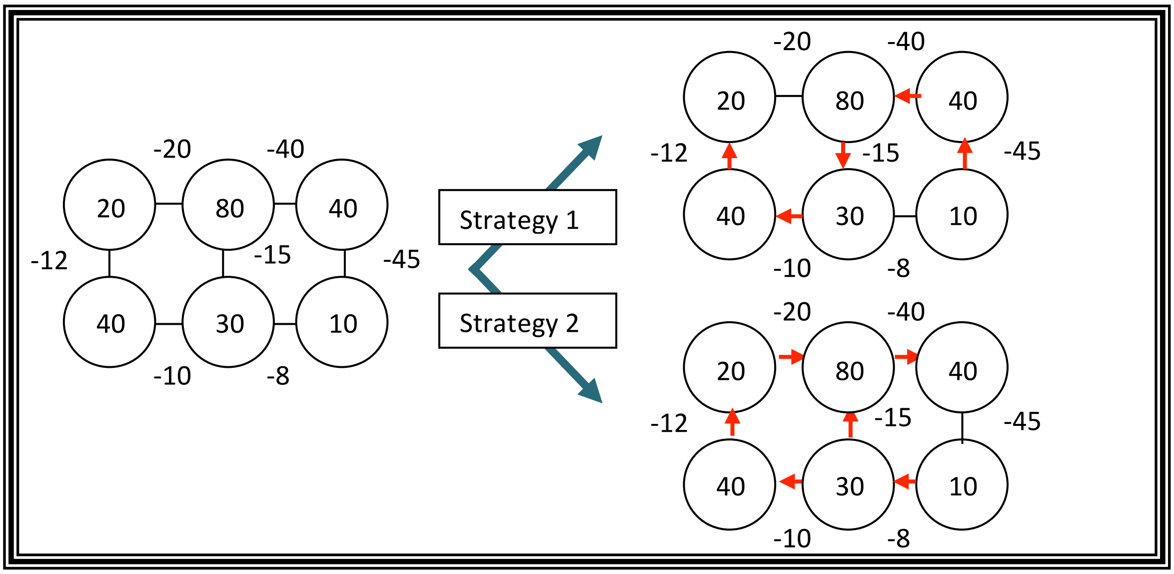

Figure 1. Conceptual example with six extraction units, where two strategies are shown.

The research summarized in this paper shows two novel and integrative tools for underground mining. It considers the mine planning production optimization and the schedule of the infrastructure development.

The first tool is called BOS2Underground, based on Blending Optimizer Sequencing and Scheduling (BOS2). This tool incorporates the sequencing as an output rather than an input, and is subject to a group of geometrical, precedence and logical constraint to generate the best feasible sequence. It also considers the global mining system capacity and the capacity per mining system component. The second tool is called Underground Development Sequencer and Scheduler (UDESS). This offers to optimize the infrastructure development with a consideration towards mining production rates.

STATE OF THE ART

During the last twenty years optimization has been incorporated as a tool for mine planning. In this sense, the latest and most important work will be reviewed to understand what has been researched.

Chanda (1990) used a computerized model for short-term production scheduling, combining simulation with mixed integer programming. The problem with drawpoint scheduling for production was studied. The goal was to reduce as much fluctuation as possible between periods of the average grade drawn. This model considers geometric constraints between drawpoints. (For example: precedence).

Jawed (1993) used another model with the same objective function with a focus on operational constraints, manpower requirements, extraction capacity, ventilation requirements, plant capacity, and lower bounds on extraction quantity. The work was prepared for a room and pillars mine.

Trout (1995) presented a model to optimize the mine production schedule. He maximized NPV, and the model was applied for sublevel stopping with backfill. The sequencing was considered, but geometric constraints of sublevel stopping sequencing, permits more geometries than in panel or block caving cases. This model is a good starting point; however, precedence constraints and capacities should be modified. Also Carlyle and Eaves (2001) carried out a similar study for the Stillwater Mining Company.

Rahal et al. (2003) used mixed integer linear programming for block caving to solve an optimization problem. The deviation from the ideal draw profile was used as an objective function. Constraints of capacity, precedence, material handling and maximum and minimum draw rate levels were considered.

Kuchta and Newman (2004, 2007) presented an optimization model to determine an operationally feasible ore extraction sequence that minimizes deviations from planned production quantities. Aggregation was used to optimize long-term production planning at an underground mine. The solution was applied for a sublevel caving mine (Kiruna) with geometric precedencies defined in one direction, horizontal (enough for sublevel caving, but not enough for block caving or sublevel stopping).

Rubio and Diering (2004) solved another optimization problem, by maximizing NPV for block caving. Two slices were used to simulate columns in a discrete vertical model and the objective function of the Rahal paper was tested. The model used precedence constraints, defined only for immediate neighbors. Geometrical precedence, considering the period in which the predecessor drawpoints are mined, was not analyzed.

Sarin and West-Hansen (2005) solved a planning optimization problem with mixed integer linear programming. NPV maximizing was used as an objective function and penalties for deviations in production and qualities were applied. The method was developed for room and pillar and longwall mining systems. The model contained capacity, sequence (constraints for immediate neighbors) and construction constraints.

Queyranne et al. (2008) presented a model for block caving that maximized NPV and used the capacity constraints of mine production, the maximum opened and active drawpoints and the neighborhood to continue production. Binary variables were considered and drawpoints can only be active for a determined number or periods. The constraints of neighboring drawpoints do not consider a range of time to mine them, but all neighbors have to be mined in the same period. However, the model does not have a capacity constraint per drawpoint.

O'Sullivan et al. (2010) solved a long-term extraction and backfill of an underground mine by deciding which and when to extract or backfill each area, depending on the global availability of material to refill, as well as simple relations for geotechnical stability. By putting all the production tasks in a gantt chart that generates more constraints then desired, a time heuristic was used to solve the large model. The variable is binary and does not have control over the eventual idle times.

It is necessary to understand that over the last twenty years the underground mine planning research has been focused on mineral extraction. The most difficult issue has been considering all the factors that have to be rechecked in the caving case.

THE MODELS

1. BOS2Underground

This model attempts to incorporate sequencing and capacity constraints, locating the sequence in time. The model is based on BOS2 (Vargas et al., 2009), which was developed in Delphos Laboratory for open pit mining. The constraints in the model were mining and processing capacities, geometalurgy, stocks, and geometric constraints. It was necessary to adapt the model for underground caving mining and adding some new constraints.

BOS2U includes an objective function and different constraints that consider precedence, logical relations, global capacity, capacity per components (shaft and crusher), minimum AL mined neighbors required to mine a block and a maximum advance per period to control dilution. All these topics and the details of the model have been published recently (Smoljanovic, 2011).

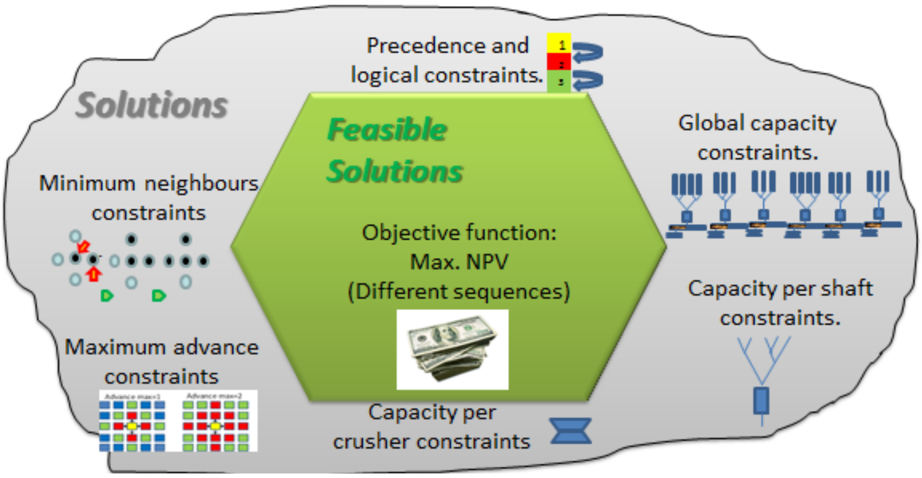

Figure 2. Objective function, variables and constraints of the BOS2U model.

The problem is summarized in Figure 2. In particular, the constraints minimum neighbors and maximum advance induces the sequence and they permit that the sequence corresponds to a panel caving method. "Minimum neighbors" is a constraint that considers a neighbors subset C of block B. To extract B, all blocks contained in C should be mined in time Δ. Maximum advance is a constraint that permits to extract neighbors until determined extent, considering the perpendicular axis to the front cave line in a period that permits to control the dilution and give an opening continuity for production.

2. UDESS

This model was developed in Delphos Laboratory in 2011 as a new line of research that tries to solve the mine development problem by transforming all the "segments" (related to drift or infrastructure) of a mine layout in activities that have the necessary attributes to prepare a model to be optimized. The attributes of the activities are a maximum and minimum development rate, a cost or profit for this activity, required resources to get the maximum and minimum development rate (equipment, materials, air ventilation, workers, etc.) and physical and operational precedence. Physical precedence orders the activities in the space according to the mine access, while operational precedence orders the activities by a logical criterion according to the associated processes (for example the crusher to draw mineral shown in Figure 3).

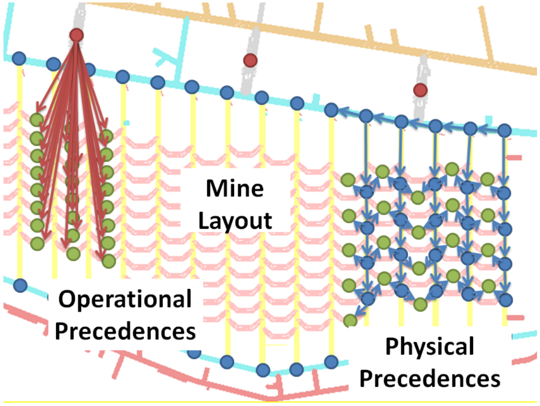

Figure 3. Physical and Operational Precedence.

The model considers maximizing the net profit as the objective function by implementing continuous variables and constraints related with the precedence, with the available resources to be distributed in all the activities, global capacity of mine capacity in plants and paths. Path constraints try to add the time consumption on each activity on every period so idle times do not appear. Moreover, to solve the larger problem it was necessary to make a time heuristic to get to a final schedule with small time periods over the entire lifetime of the mine. All the details and explanations of the model have already been published in APCOM 2011 (Rocher, 2011).

Figure 4 shows the cycle to achieve the optimized solution. It is important to note that the step involving the transformation of a CAD layout to activities was done using commercial design software, (in this case MINE2-4D).

While the text file introduced to UDESS is optimized, one of the result tables can be reintroduced in BOS2U and another can be reincorporated to MINE2-4D. This will insure the overall process considers the two main components of mine planning and gives a global optimum.

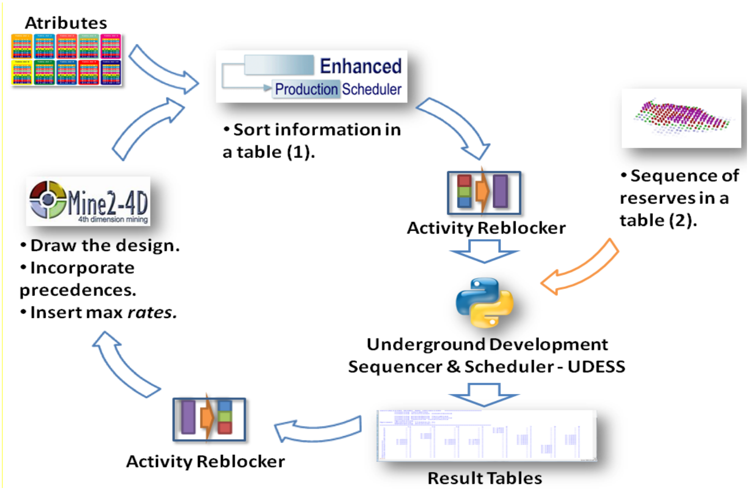

Figure 4. UDESS optimization cycle.

ANALYSIS WITH BOS2Underground

The case study is a mine that has a production rate of 30.000 tons per day (tpd). The layout has 332 drawpoints. The considered exploitation unit will be a drawpoint with the idea to model a panel caving method. Currently the sequence has already been developed, but the idea is to show how the results vary when the mining system is changed. Production is delivered to 4 crushers located on the ore body footwall. Figure 5 shows a three dimensional view of the mining system, which has four, 10.000 tpd crushers and one load-hawl-dump (LHD) per cross-cut. The last system is the real case, and the layout was tested with different mining systems. The systems are classified by crusher capacity in three groups: Group E: 4, 5, and 6 crushers (10.000 tpd each one), group F :10, 11 and 12 Chutes to a big crusher (5.000 tpd each chute) and group G: 3, 4 and 5 crushers (12.500 tpd each one).

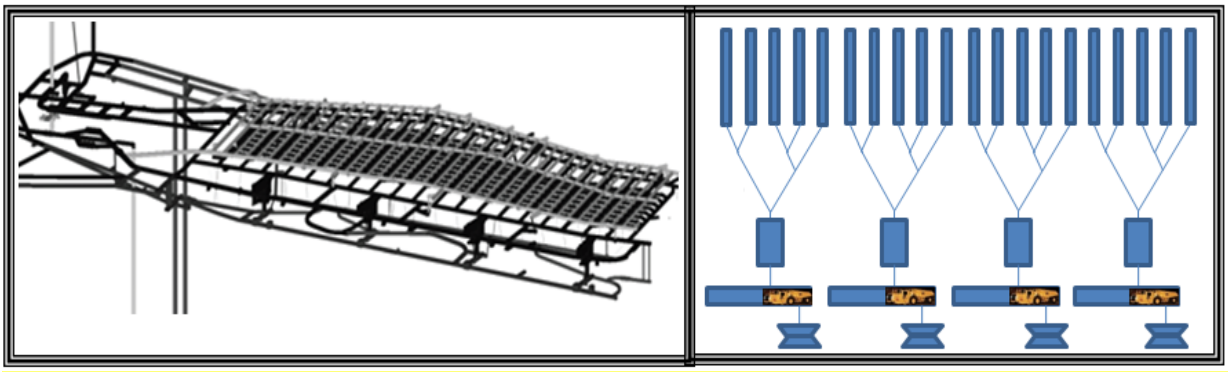

Figure 5. Case study mining system.

1. Inputs at BOS2U and considered Mining System.

The following table (Table 1) shows the required inputs to solve the model:

Table 1. Principal static parameters used in the model.

	Value	unit
Production	30	ktpd
Planning horizon	13	periods
Discount rate NPV	10	%
Maximum advance	5	dpt/period
Minimum neighbors	6	dpt
Periods to mine the minimum neighbors	2	periods
Periods to mine a drawpoint.	3	periods
Minimum exploitation per column	30	%
Capacity per drawpoint	80	ktpy
Capacity per crosscut	3,000	tpd

2. Results.

Figure 6 (left) shows the best production plan in each defined group with a clear plateau which lasts six years, considering a horizon planning of 13 years. The grades decrease because the optimization was performed with NPV as the objective function. The mining system reaches the production in the three cases perfectly.

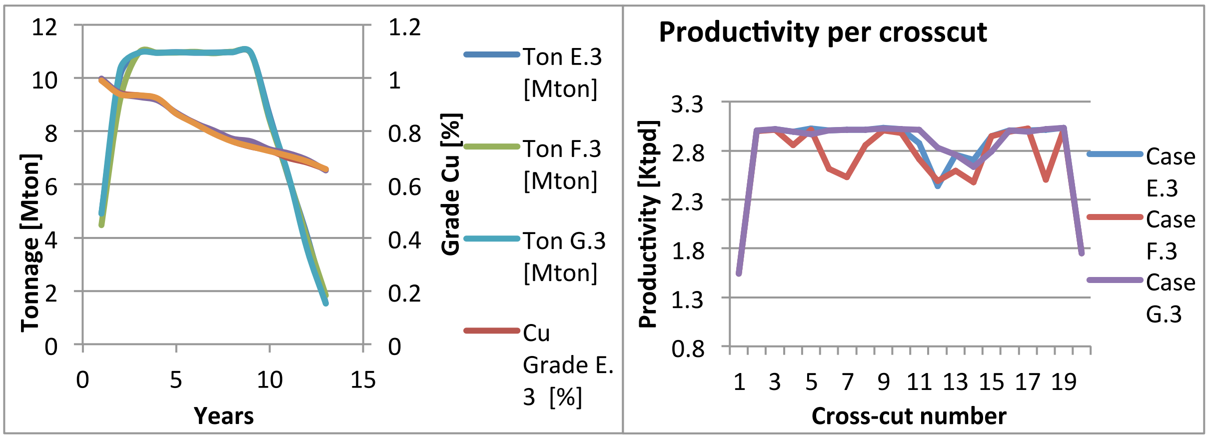

Figure 6. Production plan for the considered mining system.

Figure 6 (right) shows cross-cut performance. In relation to the maximum production per LHD per cross-cut not all the LHDs reached the capacity. On the other hand, in the case of the crushers the capacity was reached in most of them. The last idea indicates an imbalance between LHD and crushers, so these components should be balanced to obtain the best performance. Case F presents the worst production performance; due to this case this mining system has more constraints than the others. The relation between chutes and cross-cut is stricter. However the curves shown are regular enough to accept the behavior as regular.

Table 2. NPV results best and worst case per group

Case	E	F	G
Best [MU$]	1,123	1,105	1,124
Worst [MU$]	1,088	1,110	1,088
Difference [MU$]	35	5	36
Perc. Diff. [%]	3.1	0.5	3.2

Finally the NPV results per group are shown in table 2. Important differences can be noted between group F and the other two groups. Firstly, in case F the lowest value, t, is the best value, but the gap between the worst and best value for case F is the lowest. This is due to the fact that the three cases in group F are very similar. Secondly, values in the cases E and G are similar, but with a different number of crushers. Note that the NPV is directly related with sequence, so if the system changes the sequence changes.

ANALYSIS WITH UDESS

1. Testing the hypothesis of influence of the mining development in the production plan

106 activities were run with a time horizon of 60 monthly periods of a sublevel open stoping (SLOS) mine. The 106 activities included the drifting development, stopes drilling and extraction of the ore to complete all the mine operations. Within the activities, the equipment considered is a Jumbo drill for drifting, a Simba drill for radial drilling and a LHD for ore production.

The orebody consists of three vertical and parallel veins with each one having three levels of stopes. The main access is a ramp that connects the first ore body. From this ramp, drilling and production galleries are constructed for each one of the three levels mentioned. Each level (in each ore vein) contains three stopes that are extracted with a different profit and unclear trend. A set of galleries are connected from the first to second orebody, which tries to replicate the infrastructure exposed in the first case with the same characteristics and number of stopes. Eventually, the infrastructure connects with the third body in the same system to complete the entire mine. (Figure 7).

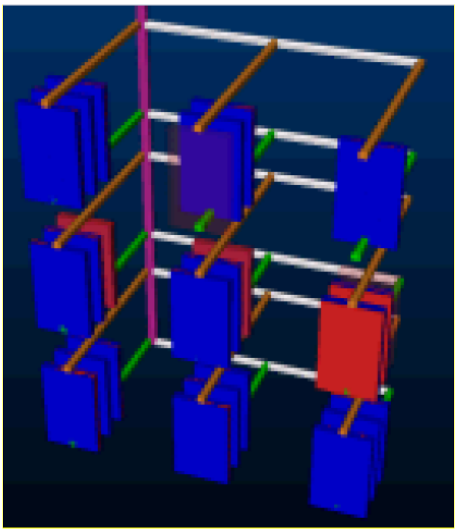

Figure 7.Sublevel open stoping layout

a. Results varying the available resources.

When the available resources for the project change, such as equipment and material for support, the only effect would be that the whole mine increases its life. However, this does not change the order of the activities. Since the resources are completely exhausted, the sequence of production changes its geometry and main direction. This is better, but not always evident.

b. Results varying the drifting speed.

This test consists of putting a variation of drifting speed for development activities. As shown in table 3, with some rates there is a common sequence (40 and 70 percent of speed). When extracting the first stopes level of each body and then move deeper, preferring to develop the horizontal galleries and at the end the decline ramps at first. By contrast with a higher drifting speed than stated before, drastic changes appear, preferring to extract all the ore from a particular vein and then develop the drift to connect the mine with the following vein due to higher net profit. Finally, with an even greater drifting speed, it is possible to select specifically which stopes will return higher values and eventually get a decreasing grade profile, so the geometry and sequence of opening stopes changes.

Table 3. Variation in the order of exploitation of stopes changing the drifting speed.

	Level	Drifting Speed				
		40%	70%	100%	130%	160%
Body 1	HIGH 3	1	1	1	1	24
	HIGH 2	2	2	2	2	1
	HIGH 1	3	3	3	3	2
	MED 3	10	9	7	4	5
	MED 2	11	10	8	5	6
	MED 1	16	26	22	6	26
	LOW 3	26	16	20	7	19
	LOW 2	18	17	12	8	9
	LOW 1	19	18	13	9	10
Body 2	HIGH 3	7	6	27	10	27
	HIGH 2	4	4	4	11	3
	HIGH 1	8	8	23	12	20
	MED 3	12	11	9	13	7
	MED 2	15	14	11	14	16
	MED 1	17	15	25	15	21
	LOW 3	24	24	19	16	17
	LOW 2	20	19	14	17	11
	LOW 1	23	21	16	18	14
Body 3	HIGH 3	9	7	6	19	23
	HIGH 2	5	5	5	20	4
	HIGH 1	6	25	26	21	22
	MED 3	13	12	10	22	8
	MED 2	14	13	18	23	15
	MED 1	27	27	24	24	25
	LOW 3	25	23	21	25	18
	LOW 2	21	20	15	26	12
	LOW 1	22	22	17	27	13

2. Panel/Block caving mine with a defined production plan

1454 activities were run with a time horizon of 30, six-monthly periods of caving mine. The exploitation units are 332 drawpoints spaced around the entire production level. The available controlled resource has the following required equipment: Jumbo, Simba, LHD, shotcrete machine, Bolter Machine and Raise Borer Machine.

The purpose is to start from a defined production plan and optimize the entire project. The first evaluation verifies if the plan is feasible with the given parameters. The next evaluation determines if the plan has some flexibility to search the best option of extraction given the mining design layout.

Figure 8 shows the obtained production plan considering these inputs and varying the drifting speed. The production plan has little perturbation considering differences between the cases. In the case of 80 percent of the original maximum advance rate, it has to start a year later than the basic case. In the case of 20 percent of the original maximum advance rate, the mine can be opened more quickly. In general, this model has more flexibility and it can make some changes to get a better total value.

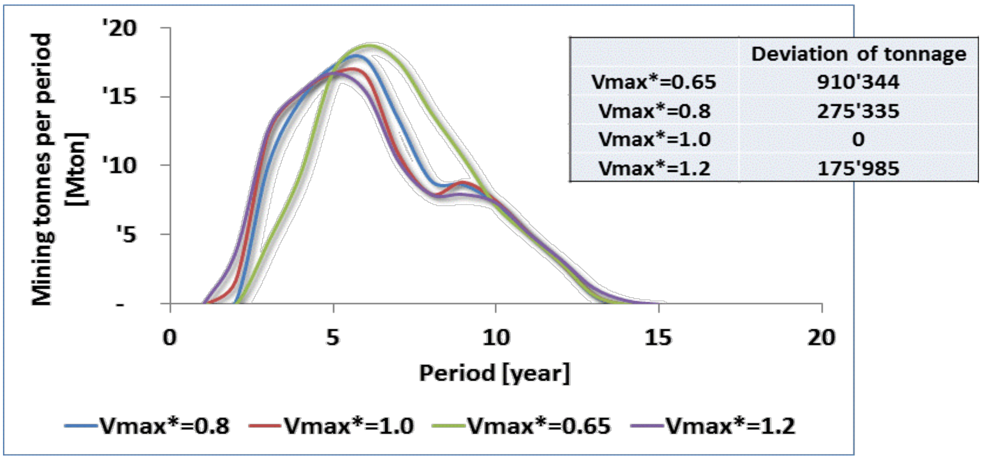

Figure 8. Resulting production plan from the optimization varying the drifting speed.

All these cases have some differences of how much tonnage extract from each drawpoint in each time. The majority of the cases keep the same sequence, excluding the case of 65 percent of the original maximum advance rate. In this case the ore is not drawn equitably in all sectors.

CONCLUSIONS

In the case of BOS2U the material handling system has important effects that define the results. If the mine planer does not incorporate this, the sequence could be completely different to the obtained with the material handling system considered, because the developed plan does not necessarily respect the constraints. The mine planner should test different material handling systems with accordance to the real possibilities. The options should not be too overwhelming, but to select the best system it has an important retribution in the final results (in value, depending on the objective function).

In the case of UDESS the optimization was reached incorporating connections and accessibilities. The proposed tool could be used to determine bottle necks, critical paths and infeasible solutions in a short time with a lot of variables and constraints. UDESS considers the sequence of the set of exploitation units connected as an output.

The opening sequence is in accordance with the objective function. This sequence is a perfect reference or guide for mine planner to have the best strategy for the mine with the possibility to do different tests in a short time. The sequence should always be a result of the set of conditions. (For the two models)

The best result will be reached when production and infrastructure present a congruence to solve the optimization problem. The production plan could be very different if the mining development is considered. This paper presents two potent tools that, if combined properly in an engineering cycle, will obtain a feasible and robust solution. The solution considers the interaction between the two mentioned strategies, generating a realistic plan.

ACKNOWLEDGEMENTS

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