Optimization of Mining Planning in Block/Panel Caving Mines Including Development Activities

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ABSTRACT

Mine planning in underground mining determines where, when and how to extract the mineral considering technical and economic factors. Generally, the extraction and development planning are performed separately. First, the production plan is generated and once the production goals are fixed, the development plan is generated in order to support the production plan.

This mine planning procedure is sub-optimal because there is no guarantee that the NPV value will be achieved. Therefore, it is necessary to consider the development rate to generate a feasible mining plan that considers the activities of construction and preparation of the necessary infrastructure to comply with the proposed mining plan.

This work aims to solve the underground production problem of a Block / Panel Caving mine considering development and extraction activities simultaneously. The results show that this approach allows obtaining an optimal mining plan, which addresses, simultaneously, the preparation and production activities. This plan optimizes the mineral reserves consumption strategy considering a development and production rate per period, draw rates by caving condition and opening of drawbells strategy.

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INTRODUCTION

Mine planning is the process of mineral engineering that transforms the mineral resource into the best productive business (Morales et al, 2012). It allows a constant search of value, varying mining designs, extraction rate, cut-off grade, extraction and development strategies. Therefore, mine planning establishes the value of the business and answers the questions: when and how to extract the mineral considering technical and economic factors.

BACKGROUND

One of the most important aspects of mine planning in underground mining using caving method is to define the order of extraction of ore columns while looking to extract the highest grade at the beginning to maximize the total NPV. For this to occur, it is necessary to have an infrastructure that allows the recovery of the broken ore at the drawpoints. Therefore, both the order in which the blocks will be extracted and the construction of the productive levels that ensure the access and extraction of the mineral must be taken into account.

The above means that the overall mine planning process is complex, hence, it is a common practice to decompose the process into different tasks and thus the overall process and specific plans for given levels are constructed independently and more easily. Unfortunately, this disaggregation of the planning process into different steps means that the final schedules do not necessarily capture the maximum value of a project. Indeed, as the steps in the planning process are carried out sequentially, decisions are made with aggregated information and models that do not capture the complexity of forthcoming steps and, thus, subsequent decisions are subject to the initial one, hence the overall result may be suboptimal.

An example of the disaggregation is the separate realization of the extraction planning process and the construction preparation in mining methods by caving. Indeed, the motivation of this paper comes from the decoupling of the extraction scheduling (that is, what is to be mined from an underground mine and when), from the development scheduling (which is the set of construction activities and infrastructure to be carried out during the extraction scheduling and corresponding production goals). More specifically, the motivation was born when this decoupling caused an excess of investment in workings because the prepared area would not have been used in the period or would have affected the planned extraction due to lack of prepared area or due to the stability problems as a result of poor management of the cave back. For instance, Diaz and Morales 2008 indicated that in 2002 they had a 61% fulfilment of development and a 70% fulfilment of production.

This work aims to propose a methodology that allows the planning of the optimization of a mining plan that considers both the extraction and the mine development strategies. A scheduling software called UDESS was used, which is based on an optimization model for scheduling activities optimally under capacity and precedence constraints, among others. The construction and production of a Panel Caving mine (of a real operation) was modelled and analyzed. The objective function of the optimization was the maximization of the NPV in a given time horizon subject to sequential constraints (precedence) and operational constraints.

UDESS

The UDESS software was developed by the DELPHOS Mine Planning Laboratory at University of Chile. It is a scheduler and sequencer tool based on mathematical programming that is very versatile in the nature of the problems that it can addressed, being able to cover scheduling in underground mining, transition mining and open pit. The software is currently used for academic and research purposes. UDESS works under a concept of activities or tasks, which are related by precedence requirements, forcing the commencement of certain tasks to be limited by the achievement of others.

Tasks in UDESS have a certain economic value and consume resources (e.g. team hours) to achieve them. The software then schedules the tasks to produce the maximum benefit (or minimum cost).

The output of UDESS corresponds to a Gantt chart specifying how much progress in each of the activities has been defined over the planning horizon. This output is then exportable to Excel for analysis and implementation.

METHODOLOGY

Main modeling aspects

Some of the main modeling aspects that are related to UDESS are:

- ✓ Maximum Rate: indicates the maximum feasible amount of an attribute that can be performed at any time for any activity (production unit, section of a tunnel, etc.). In this model, we consider the maximum percentage of progress of the activity to be performed per period.
- ✓ Cost or profit: these variables are the goal functions to be maximized. Positive values (profits) are associated with production activities, while negative values (costs) could be associated with the development activities (notice that, depending on the ore content, there could be production activities with a net value that is negative).
- ✓ Resources: these are essential for the correct or real analysis because they indicate which materials, machines, workers or time are necessary to complete an activity. There exists (at each moment) an overall availability of these resources that must be shared between the activities that require it.
- ✓ Physical Precedencies: these relations define what developments must be constructed in order to gain access (physical) or allow the commencement of other activities. These constraints depend on the layout of the mine, which is assumed to be fixed.
- ✓ Extraction Capacity Constraints: these state the parameters that have to obey within certain mining methods. In block / panel caving there is a draw rate, which controls flow of muck,

and the draw ratio. This will control the dilution entry point and damage to the production level. Most importantly, it gives a space consistency in relation to the production activities.

Modeling construction and production of Panel Caving in UDESS

The main assumptions for the modeling in this paper are:

- ✓ The production levels included are the extraction level and undercut level, but transport and ventilation levels are considered to be developed in early stages of the project and therefore they are not included in the planning being optimized. This decision does not affect the methodology since it does not have a significant impact on the problem solutions.
- ✓ The layout (in particular the best economical floor, economic ore column height and footprint) are known information.
- ✓ The block model used was diluted with the Laubscher Volumetric Dilution methodology with a dilution entry point equal to 45% and an interaction height (HOZ) of 80 meters.
- ✓ The mine will be operated using Conventional Panel Caving method, with a layout of the El Teniente production level with a 15 x 20 mine design.

As the UDESS tool works based on activities, both block model and development-mining tasks are considered as activities. Figure 1 shows a workflow used to support the methodology.

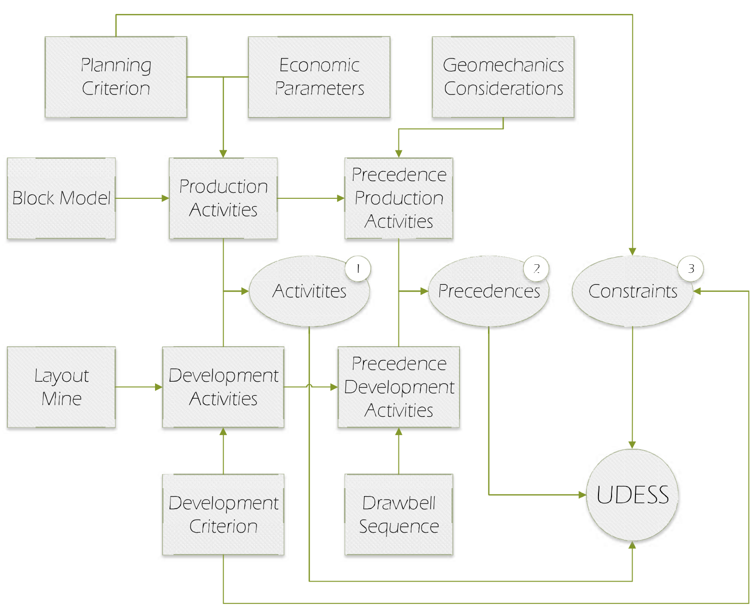


Figure 1. Conceptual model in UDESS

Step 1: Definition of Activities

✓ Extraction Activities

Production activities are defined from blocks containing the block model (blocks with attributes of tonnage, grade, recovery, etc.). Each block has a profit assign to it and each extraction activity will have an associated income or cost (Table 1). Each extraction activity will have a maximum rate of development, which represents the draw rate of each block according to the height and state of the ore column (planning criterion).

Table 1. Attributes in the input block model.

Activity	X	Y	Z	Tonnes [ton]	Ley [%]	Max_Rate [times/period]	Income [USD]
Block_i	x_i	y_i	z_i	T_i	L_i	MR_i	B_i

✓ Mining Development Activities

Reinforcement and development activities are defined based on the tasks that must be fulfilled to build productive levels (Table 2). These tasks are sequential and, from the development criteria, each activity will have attributes, such as, the drive length or reinforcement amount, and a cost to execute them. In addition, each activity will have a maximum rate of the development that represents its performance (Table 2).

Figure 2. Mining Development Activities by Productive Level and Macro-Stage

Table 2. Mining Development and Reinforcement Activities

Activity	Max_Rate [1/period]	Costs [USD]	Lenght [m]	Amount
Drive_Production_1.1	MR_i	-B_i	ℓ_i	a_i

Step 2: Definition of Precedencies

Precedencies correspond to a type of constraint that represent minimum requirements to start a certain activity in terms of the successful conclusion of others. We use precedencies to model several aspects of the construction and production in the Panel Caving operation.

✓ Precedencies between Mining Development Activities and Extraction Activities

Precedencies between Mining Development Activities and Extraction Activities are shown in Figure 3. These precedencies are in order to start the extraction after opening the Drawbell line.

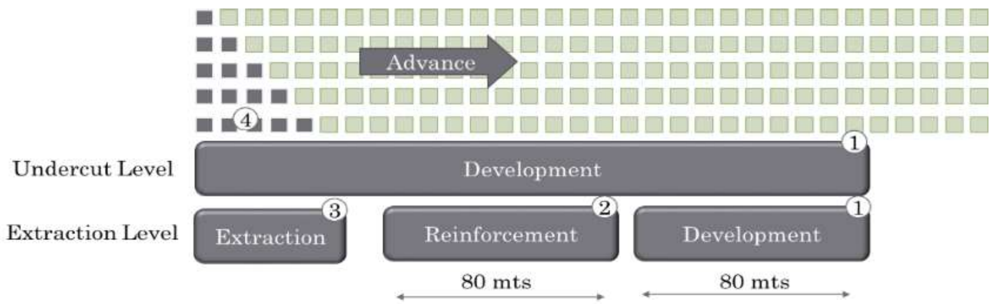


Figure 3. Level Productive Precedence

✓ Precedencies Mining Development Activities

Precedencies inside each productive level are defined. For all levels, this type of restriction is used to model the activities sequence to be followed in the construction of all levels. For instance, at the extraction level, it is required that the mining development should be 80 meters ahead of the definitive reinforcement zone (measured on the horizontal axis) to avoid operational interferences (Jamett & Alegría, 2014). In turn, the final reinforcement must be 80 m ahead of the cave front to ensure staff safety (see Figures 3 and 4).

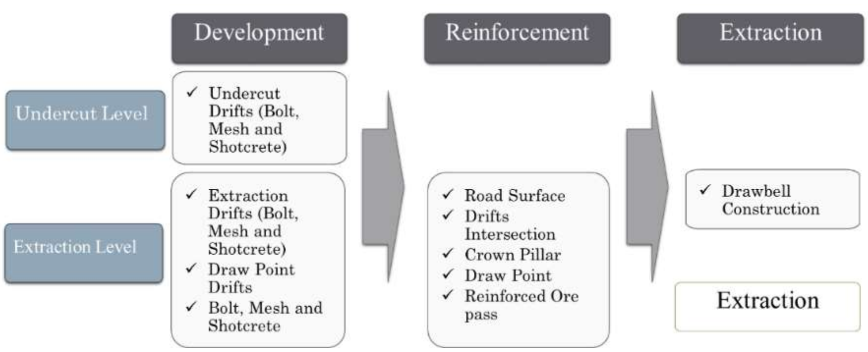
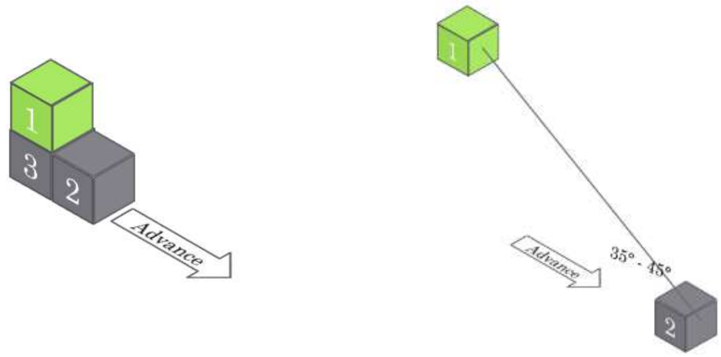


Figure 4. Precedencies between construction activities

✓ Extraction Angle

This type of restriction is used to model the vertical extraction of a rock column and the caving propagation considering geometric aspects (extraction angle: 35 ° - 45 °) (Cornejo, Pinochet & Caviedes, 2016). In addition, it allows controlling the dilution entry.



a) 30% Height Ore Column b) Ore Column Rest

Figure 5. Precedencies: (a) 30% height Ore Column and (b) Rest of Ore Column

CASE STUDY

A case study was selected to implement the proposed model. This case study is based on information from some projects and mines in operation but does not represents a particular mine. The main assumptions applied to the study are as follows:

Mining Design and Mine Layout

The mining method chosen was a Panel Caving with conventional undercutting and a footprint of basal area of 300 m x 240 m. Extraction level layout type El Teniente was selected and an extraction mesh of dimensions 15 x 20 m with sections drifts 4.1 m x 4.1 m was considered.

Mining Development Plan

Mine design for the development plan was proposed; the dimensions and quantities of workings are shown in Table 3.

Table 3. Development Plan and Performance

Level	Workings Mine	Amount [unit]	Length [m]	Output
Undercut	Drive	9	3,962	100 m/month
	Stub Tunnel	3	725	100 m/month
Extraction	Drive Extraction	9	4,000	150 m/month
	Drive Drawpoint	22	4,156	150 m/month
	Drawbell	120	-	730 m/unit
	Ore Pass	18	30 (each one)	1.2 unit/year
Reinforcement Extraction Level	Crossings Drift	154	-	9 unit/month
	Road Surface	-	3,260	120 m/month

	Pillar Reinforced	-	2,440	3 unit/month
	Drawpoint	240	-	6 unit/month

Extraction and Undercutting Rate

The extraction rate and undercutting rate are estimated according to Equations 1 and 2, respectively.

$$E_e[tpd] = A[m^2] \cdot V_{ext}[\frac{t}{d \cdot m^2}] \cdot d\ [\%] \quad (1)$$

$$V_p[\frac{m^2}{year}] = \frac{MPC\ [ton/year]}{H[m] \cdot \gamma[\frac{t}{m^3}] \cdot d[\%]} \quad (2)$$

For the case of the production rate, a mathematical expression proposed by Araneda and Gaete (2004) is used; the active area (A) considered was 30,000 m^2, the effective draw rate (V_{ext}) was considered at 0.5 t / m^2-day and the availability of drawpoints at 80%. Therefore, the estimated production was 12,000 tpd.

For the case of the undercutting rate, it was estimated according to the expression proposed by Ovalle, 2012. The rate of mining development was considered as the undercutting rate with an extraction rate of 12,000 tpd, average density of 2.7 t / m^3, a removable economic height of 250 meters and an operational recovery of 80% area. The average undercutting rate was 8,000 m2 per year.

Draw Rate

Table 4 shows the draw rate used for the study case. An extraction rate of 0.25 t / m^2 per day was defined to reach the critical area required to generate caving. Then, the remaining rock columns used a velocity profile of 0.35 to 0.75 t / m^2 per day.

Table 4. Draw Rates depending on extraction height

Draw Rate (ton/m2-dia)	Column height (m)	Status
0.25	0 - 36 mts (Critical Area)	Initial Caving
0.35	0 - 36 mts (No Critical Area)	Breaking
0.55	37 - 72 mts	Broken Column
0.75	72 – 250 mts	Steady

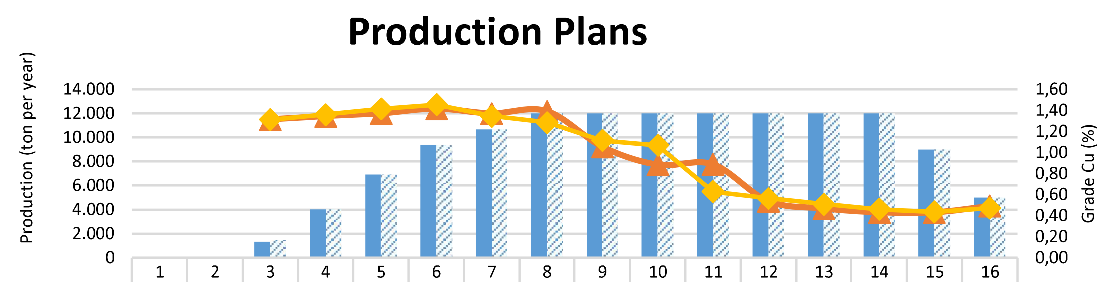
Two different simulations were performed to determine the impact of joint scheduling or construction and production:

- ✓ Case Study 1: Simultaneous scheduling of the Mining Development, the Reinforcement and the Extraction
- ✓ Case Study 2: Scheduling of the Extraction only, without taking into account Mining Developments (except for capacities).

RESULTS AND DISCUSSION

Scheduling Plan

Figure 6 shows the production plans obtained for both cases studies. The extraction rate of both shows no differences. Regarding the copper average grade, they present similar decreasing behavior throughout the extraction horizon. From the economic point of view, the net present value for case study 1 is 514 million dollars and for study case 2, the NPV is 683 million dollars.

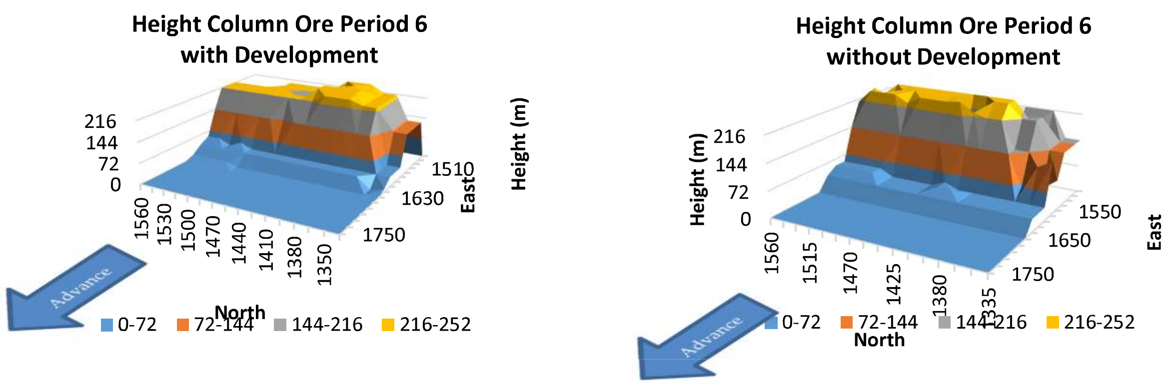


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
TPD, Caso Study 1	0	0	1.303	4.029	6.925	9.389	10.687	12.000	12.000	12.000	12.000	12.000	12.000	12.000	9.000	5.000
TPD, Caso Study 2	0	0	1467	4029	6925	9389	10687	12000	12000	12000	12000	12000	12000	12000	9000	5000
Grade, Caso Study 1			1,31	1,34	1,37	1,41	1,37	1,39	1,05	0,88	0,89	0,54	0,47	0,43	0,43	0,49
Grade, Caso Study 2			1,31	1,36	1,41	1,45	1,35	1,28	1,12	1,07	0,63	0,56	0,51	0,46	0,43	0,47

Figure 6. Production Plans for Case Studies 1 and 2.

Case study 2 was simulated without development and preparation constraints. This added a NPV of $ 683 million. However, when the mining development and reinforcement were imposed, the value decreased considerably. This situation is because the execution of this production plan in real life is unfeasible and it does not consider the constructability restrictions. In other words, production stage proposed by the model cannot be executed due to lack of mining development.

Figure 7 shows the extraction envelope for Case Studies 1 and 2. In both cases, it can be seen that the geometric constraints are satisfied and that the extraction angle is maintained between 35 ° to 45 ° in regime condition (Contreras, Cornejo & Caviedes, 2016).



a) Case Study 1: Extraction Envelope Period 6

b) Case Study 2: Extraction Envelope Period 6

Figure 7. Ore Column Height, period 6.

Scheduling of Developments

Table 5 shows the workings and activities to comply with the infrastructure required for mineral extraction. At the extraction level, the first activities developed are the drifts extraction and drawpoints drifts, which reaches its maximum performance in the early years. The drawbells are the last activities to be carried out, as they give the step to mineral extraction. As of period 10, no development and reinforcement activities were performed.

Table 5. Development and Preparation Plan

DEVELOPMENT AND	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12-16**	**Total**
Development													
Extraction Drive (m)	1,686	1,800	1,156	1,713	622	0	0	0	0	0	0	0	6,977
Undercut Drive (m)	0	0	460	92	1104	373	179	1104	512	0	0	0	3,824
Reinforcement													
Road Surface (m)	40	660	340	460	400	240	400	280	40	0	0	0	2,820
Crossing (unit)	2	33	17	23	20	12	20	14	2	0	0	0	141
Pillars (m)	23	677	340	441	412	247	400	280	23	0	0	0	2,820
Draw point (unit)	0	42	38	28	32	38	36	26	0	0	0	0	240
Extraction													
Drawbell (unit)	0	0	6	11	10	12	16	20	20	20	5	0	120

CONCLUSION

A methodology to solve an underground production problem including the development activities was proposed. The results show that UDESS allows to obtain an optimal mine plan, which addresses, simultaneously, the development and extraction activities, such as, undercut and extraction levels. This plan includes an optimized schedule of the drawpoint given a macro-sequence. Therefore, this allows the planner to obtain an integrated and feasible plan for the long- and medium-term mine planning stages. Finally, this work proposes a methodology that solves a problem of scheduling in mining methods with an integrated approach between Extraction and Mining Development (plus Reinforcement) that manages to couple both processes in the medium- and long-term mine planning. Future evaluation will include haulage level and ventilation sub-level and uncertainty.

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