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

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Mine planning in underground mining determines where, when and how to extract the mineral considering technical and economic factors. However, usually 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 so that it supports the production plan.
As it turns out, the procedure described above is sub-optimal, because there is no guarantee that the optimal 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.

1. Introduction

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

1.1. Background

One of the more important aspects of mining planning in underground mining methods by caving is to define the order of extraction of ore columns, while looking for to extract the highest grade at the beginning so that the total NPV is maximized. For this to happen, it is necessary to have an infrastructure that allows the recovery of the broken ore at the drawpoints. Then, we must take into account 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.
The above means that the overall mine planning process is complex, hence it is common practice to decompose it into different tasks and 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, former decisions are made with aggregated information and models that do not capture the complexity of forthcoming steps, and later decisions are subject to the initial one, hence the overall result may be suboptimal.

An example of the disaggregation described before is related to the extraction planning process and the construction preparation in mining methods by caving type are realized separately. Indeed, the motivation of this paper comes from the decoupling of determining 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 on in order to carry out the extraction scheduling and corresponding production goals). More specifically, the motivation is born when this decoupling causes an excess of investment in workings because the prepared area will not be used in the period or affects the planned extraction due to lack of prepared area or to cause stability problems due to poor management of the cave back. For instance, Diaz and Morales 2008 indicates that in 2002 they had a 61% fulfillment of development and a 70% fulfillment 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 strategy and the mining development strategy. For this, we use a scheduling software called UDESS that in turn is based on an optimization model for scheduling activities optimally under capacity and precedence constraints, among others. We model the construction and production of a Panel Caving mine (of a real operation) and apply it at a real case study. The objective function will be to maximize the NPV in a given time horizon subject to sequential constraints (precedence) and operational constraints.

1.2. UDESS

The UDESS software developed by the DELPHOS Mine Planning Lab 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 can be addressed, being able to cover scheduling in underground mining with massive or based methods in houses, transition mining and even open pit, which is currently used for academic and research purposes. UDESS works under a concept of activities or tasks, which are related by precedence requirements, so that the beginning of certain tasks is limited by the achievement of others.

Tasks in UDESS have a certain economic value and consume resources (eg team hours) for their achievement. 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 defined over the planning horizon. This output is then exportable to Excel for analysis and implementation.

2. Methodology

2.1. 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 this maximum development as the maximum percentage of progress of the activity to be performed per period.
- *Cost or profit*: These take place in the goal function to be maximized. Positive values (profits) are associated to production activities, but can be negative values (costs) to 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 Precedences*: These relations define what developments must be constructed in order to gain access (physical) or allow starting other activities. These constraints depend on the layout of the mine, which is assumed to be fixed.
- *Extraction Capacity Constraints*: These states the parameters that have to obey certain mining methods. In block caving there is a draw rate, which controls flow of muck, and the draw ratio already mentioned. 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.

2.2. Modeling construction and production of Panel Caving in UDESS

The main assumptions for the modeling in this paper are:

- The productive 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, economically ore column height and foot print) are known information.
- The proposed methodology will be based on the assumption that Conventional Panel Caving will operate the mine, with a layout of the El Teniente production level with a 15 x 20 mining 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.

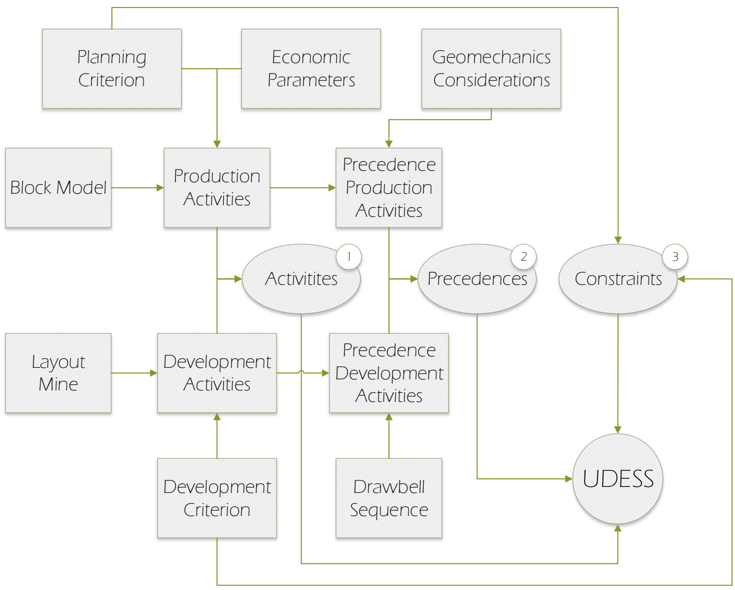


Figure 1. Conceptual model in UDESS

2.2.1. 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.). In order to economic parameters, each block has a profit and then each extraction activity will have income or cost. Indeed, 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).

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

Tabla 1. Attributes in the input block model.

- **Mining Development Activities**

Reinforcement and development activities are defined based on the tasks that must be fulfilled to build productive levels (see Figure 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. Also, each one will have a maximum rate of development that represents the performance of each one of them (table 2).

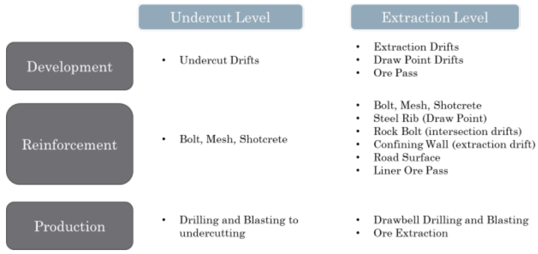


Figure 2. Mining Development Activities by Productive Level and Macro-Stage

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

Table 2. Mining Development and Reinforcement Activities

2.2.2. Step 2: Definition of precedences

Precedences 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 precedences to model several aspects of the construction and production in the Panel Caving operation.

- **Precedences between Mining Development Activities and Extraction Activities**

Precedences between Mining Development Activities and Extraction Activities are shown in figure 3. These precedences are in order to start the extraction after opening the Drawbell line.

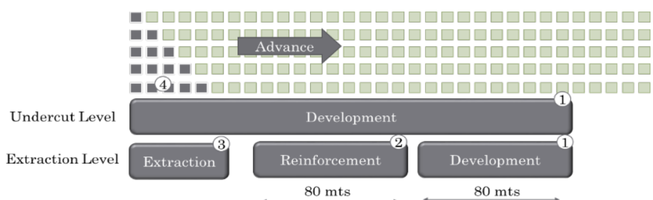


Figure 3.Level Productive Precedence

- **Precedences Mining Development Activities**

Precedences inside the 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 interference [Jamett, N, Alegría, 2014]. In turn, the final reinforcement must be 80 m ahead of the cave front to ensure staff safety (see figure 3 y figure 4).

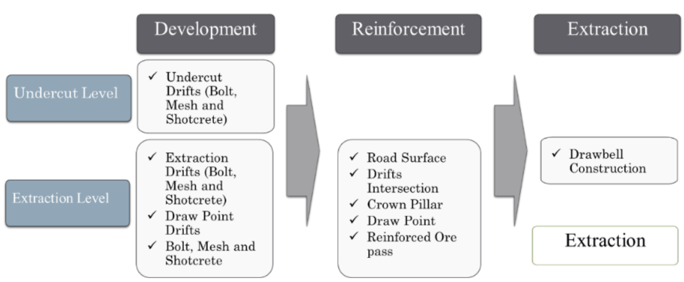
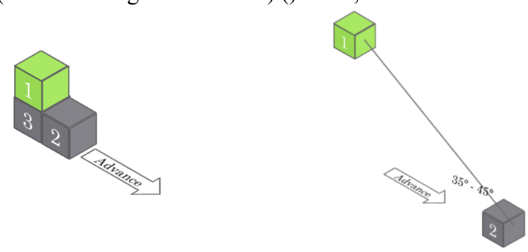


Figure 4. Precedences between construction activities

- **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 °) (). Also, it allows controlling the dilution entry.



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

Figure 5. a) Precedence 30% height Ore Column. b) Precedence Rest of Ore Column

2.2.3. Step 3: Other Constraints

The constraints used in the production stage are to reach or limit production capacity per year. In the case of the development mining activities, the constraints used also allowed to limit the drives construction (in meters/time), ore passes (units/time), extraction level reinforcement (units/time) and the drawbells construction (units/time).

3. 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, and does not represent any in particular. The main assumptions applied to the study are shown below.

3.1. 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 was selected. 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.

3.2. Mining Development Plan

It was also necessary to dimension the construction of the productive levels. In this sense, a mining design was proposed, and the dimensions and quantities of workings are shown in table 3.

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

Table 3. Development Plan and Performance

3.3. Extraction and Undercutting Rate

The extraction rate and undercutting rate are estimated in order to Equations 1 and 2, respectively. For the case of the production rate, a mathematical expression proposed by Araneda and Gaete (2004) is used; the active area (A) considered is 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 is 12,000 tpd.

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

For the case of the undercutting rate, it is estimated according to the expression proposed by Ovalle, 2012. The rate of mining development is considered as the undercutting rate and to calcule, an extraction rate of 12,000 tpd, average density of 2.7 t / m3, a removable economic height of 250 meters and a Recovery Operational of 80% area were considered. Then, the average undercutting rate is 8,000 m2 per year.

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

3.4. Draw Rate

Table 4 shows the draw rate used for the study case. An extraction rate of 0.25 t / m^2-day is 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-day.

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

Table 4. Draw Rates depending on extraction height

We run two different instances of the model in order to compare the results and see the impact of joint scheduling or construction and production:

- Case Study 1: We use the model to schedule simultaneously the Mining Development, the Reinforcement and the Extraction
- Case Study 2: In this case we Schedule only the Extraction, without taking into account Mining Developments (except for capacities).

4. Results

4.1. 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 532 million dollars and for study case 2, the VPN is 683 million dollars.
Case study 2 was run without development and preparation constraints. This added a VPN of $ 683 million. However, when the mining development and reinforcement were imposed on the problem, the value decreased considerably. This situation is because the execution of this production plan in real life is infeasible and it does not consider the constructability restrictions. In other words, production stage proposed by the model cannot be executed by the lack of mining development.

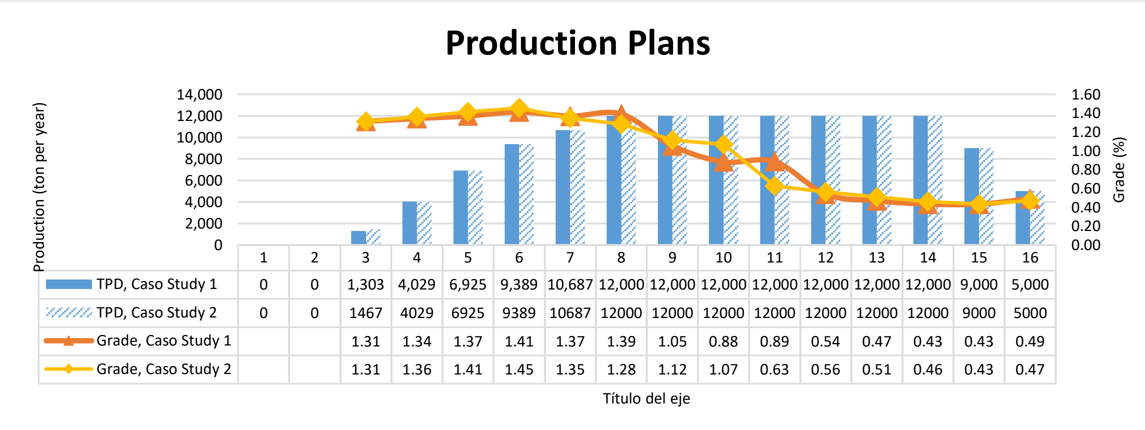
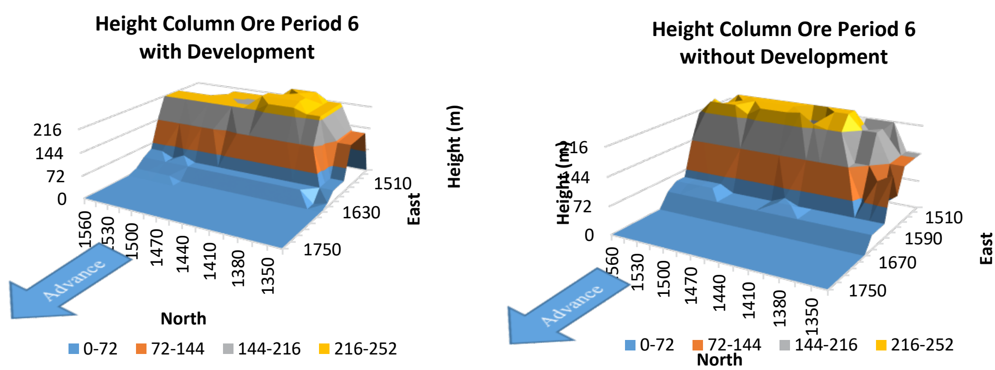


Figure 6. Production Plans for Case Studies 1 and 2.

4.2. Extraction Strategy

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, J, Cornejo, J, Caviedes, C, 2016).



a) Case Study 1: Extraction Envelope Period 6 b) Case Study 2: Extraction Envelope Period 6

Figure 7.Ore Column Height, period 6.

4.3. 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 12, no development activity is performed.

DEVELOPMENT AND REINFORCEMENT	1	2	3	4	5	6	7	8	9	10	11 - 16
Development											
Extraction Drive (m)	1,800	1,800	1,022	1,800	555	0	0	0	0	0	0
Undercut Drive (m)	0	460	230	1,063	399	56	1,104	512	0	0	0
Reinforcement											
Road Surface (m)	40	720	280	440	600	80	300	360	0	0	0
Crossing (unit)	2	36	14	22	30	4	15	18	0	0	0

Pillars (m)	40	720	280	440	520	160	300	360	0	0	0
Draw point (unit)	0	49	31	28	49	21	30	32	0	0	0
Extraction											
Drawbell (unit)	0	9	11	10	12	14	16	16	16	16	0

Tabla 5. Plan de Desarrollo y Preparación

5. Conclusions

A methodology to solve an underground production problem including the development activities is 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 give a macro-sequence. Therefore, this allows the planner to obtain an integrated and feasible plan for the long and medium term mine planning stage.

Finally, this work proposes a methodology that solves a problem of scheduling in mining methods with an integrative approach between Extraction and Mining Development (plus Reinforcement) that manages to couple both processes in the medium and long term mining planning.

Future work will be to evaluate the inclusion of haulage level and ventilation sub-level.

6. Acknowledgments

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