Multi-Criteria Optimization for Scheduling of a Bench and Fill Mine

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ABSTRACT: Traditionally, geomechanics provide parameters and criteria that are inputs to the planning process. For example, when computing the final pit, geomechanics may provide a maximum slope angles to guarantee the stability of the pit walls. This separation between the geomechanical considerations and the planning process has some drawbacks, a major one being that the impact of specific geomechanical constraints on the value of the business may not be well understood or completely overlooked.

The above is especially true in the case of selective underground methods like sublevel stoping or bench and fill, where the relation between the geomechanics and the planning is tighter and also were there is a lack of optimizing tools for mine planning. In this case, the currently available tools for the planners are closer to design or CAD tools rather than planning optimization ones.

In this work, we used UDESS (Underground Development and Extraction Sequencer and Scheduler), a tool based on mathematical optimization that has been developed at AMTC of University of Chile that allows to express activity precedences, benefits and requirements and to compute the optimal schedule of these activities based on different criteria.

The tool described above allowed us modelling the activities of a real bench and fill mining operation in a simple way and then to quickly compute scheduling for the mine. Using this, we were able to replicate existing plans for the mine and then to study how these plans change, in terms of value and scheduling, when geomechanical parameters such as dilution or stability are taken into account within the planning process.

INTRODUCTION

Mine planning emerges as a discipline that seeks to strategically deliver business options to the deposit under evaluation in different stages of the process. Depending on the deposit's conditions, and the time period to be evaluated, the number of restrictions vary. In the initial stages of the planning process there exists greater freedom to explore alternatives and evaluate the risk in technical and economic terms. Once the operation has begun, the available alternatives decrease considerably; particularly for the case of Selective Underground Mining (SUM) with reef mineralization, which considerably restricts the continuity of the extraction.

Indeed, in the case of SUM, the plan aims to follow a mineralization reef and prevent the extraction of waste. Therefore the construction of the plans becomes a complex process. According to the fundamental condition of the method, the ideal one is to extract the least amount of material possible, in order to ensure selectivity. Conversely, failing to do this implies the extraction of low or null grade material, known as dilution (Pelley, 1994).

It is clear that although feasible schedules can be obtained through different methods, only an integrated optimization ensures an optimum solution. Therefore, in this work we deal with the problem of looking for techniques to jointly optimize the geomechanical parameters and the schedule in order to maximize the value. More specifically, we will be interested on dilution.

Planning for Selective Underground Methods

The optimum design of the mine layout and the best scheduling of mining activities, with consideration to the resource constraints and economic factors taken into account, are the main guidelines that determine the search for realistic mathematical models and efficient solution approaches.

Scheduling problems for underground mining needs to define when to carry out a mining activity, where an activity might be associated with, for example, a part of the excavation of a tunnel by time unit available to the machinery required for the task. In turn, the efficiency of the production schedule and cost estimation in a mine plan will depend on its ability to assess the geological variability and characteristics of the orebody and on the experience of the team (Kazakidis and Scoble, 2003).

An evaluation of the mine-planning practices in underground mining indicates that there is no systematic method for introducing flexibility in mine planning and design. This procedure is not documented or formalized. Instead, it is subjective and depends upon the experience of the senior planner. Currently there does not appear to be any formal process to quantify the value of flexibility alternatives in the mine plan (Kazakidis and Scoble, 2003).

Dilution

Dilution is understood as the contamination of the mineral by non-mineral material during the mining process (Wright, 1983). The main consequence of this contamination is a lower grade of the extracted material, either because not all the metal equivalent is extracted or because more material than planned is extracted.

Scoble and Moss (1994) define *Total Dilution* as the sum of planned dilution (material below cutoff that is located within the stope limits) and unplanned dilution (material below cutoff that is extracted, but was located outside planned stopes).

There exist different methods to calculate the dilution that affects a stope- In our case we use the ELOS concept introduced in (Clark, 1998) and (Dunne and Pakalnis, 1996) to represent dilution in terms of a lineal density of over-excavation. This term standardizes the total volume of over-excavation of a wall along the entire extent of its area. Figure 1 shows a graphical representation of a cross-section.

In numerical terms, dilution can be express in the following way:

$$\mathrm{ELOS}[\mathrm{m}] = \frac{\text{Volume of the overexcavation of the wall}[\mathrm{m}^3]}{\text{Area of the wall }[\mathrm{m}^2]} \tag{1}$$

Equation 1: Dilution formulation by means of ELOS. Source: Henning (2007)

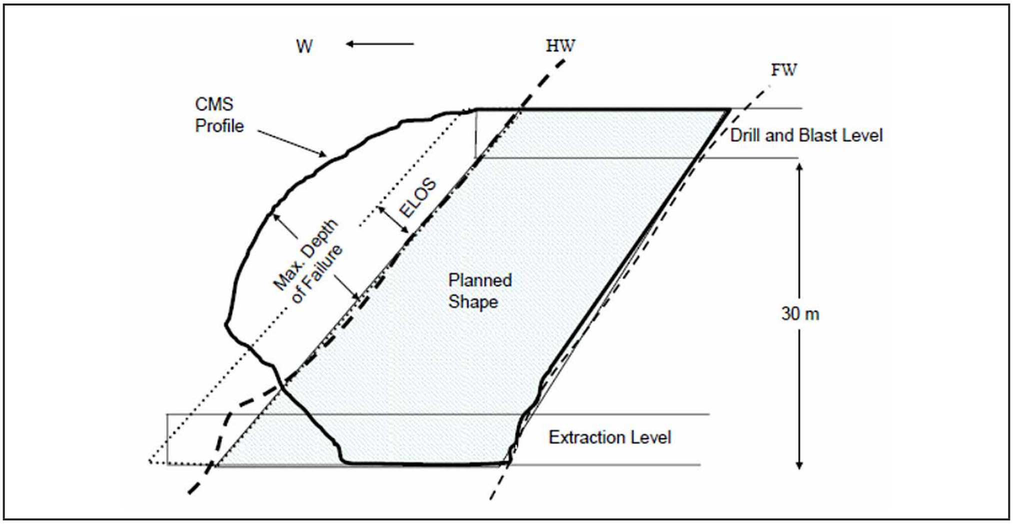

Figure 1. Cross-section of ELOS. Source: Capes (2009)

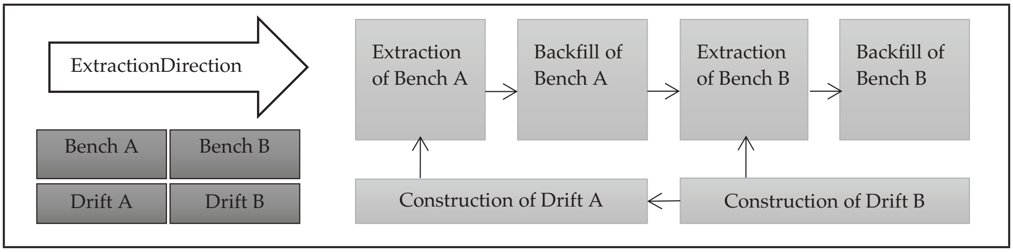

Figure 2. Mining structure and their representation as UDESS activities. On the left, two benches and corresponding drift. On the right, abstraction of same benches and drifts in terms of activities.

The Underground Development and Extraction Sequencer and Scheduler (UDESS)

In order to construct the production schedules, we relied on a computational tool developed at the University of Chile. UDESS was originally developed with the goal to schedule the production and extraction of underground caving mines, but has showed to be flexible enough to be used for this study.

UDESS takes a set of activities as inputs (for example, bench extraction, backfilling or drift development) and a set of arc precedences that specify some goals to be satisfied in order to proceed with one activity. Figure 2 shows an example of this. On the left, two benches and their corresponding drifts are drawn, as well as the overall general extraction direction. On the right, the same benches are extracted by two activities: one representing the extraction and other representing the backfill activity, while drifts require only one activity (construction). The arrows between these activities represent precedence requirements so, in this example, to start the extraction of Bench 2, the Drift 2 is constructed and also that Bench A is already backfilled.

Real structures and representation as several activities UDESS also allows to set, for each activity, different resources to be consumed in order to perform said activities. In this way, the extraction

Table 1. Assessment parameters

	Parameters	
	Value	Unit
Gold Price	1,200	USD/Oz
Mining Cost	154.48	USD/ton
Backfill Cost 1	15	USD/m^3
Backfill Cost 2	20	USD/m^3
Drill Cost	10	USD/m
Yearly Rate Discount	10	%

of a bench will use some mining capacity (for example in tonnage and/or equipment), while the backfill requires the use of others (backfill capacity and/or equipment).

The output of UDESS is a Gantt chart that specifies for each activity, the percentage to be performed at any given time-period. This Gantt chart (or schedule) is prepared in such a way that it complies with the precedence requirements and it does not use more operational resources than the ones provided, and maximizes (or minimizes) a function like NPV, total production, construction time, cost, etc.

METHODOLOGY

The first step in the methodology is to define the activities and their precedences, as well as the operational resources they use and the economic impact on the plan. In our case, we considered the following activities with attributes:

1. Drift construction, with economic value, tonnage, grade and length.
2. Bench drilling, with cost and drilling capacity usage.
3. Bench extraction, with economic value, tonnage and grade.
4. Bench backfilling 1, with cost and usage.
5. Bench backfilling 2, with cost and usage.

Next, we define the planning parameters for each of the operational resources considered. For example, the maximum tonnage to be extracted, which limits bench extraction.

In a first validation run, we set the constraints such that UDESS is forced to follow a preexisting plan, in terms of production; and then to check if the schedule produces complies with all operational constraints, in particular to verify if the precedences are set properly or not.

The next step in this work was to study the impact of different design parameters. More precisely, we studied the impact of using different bench lengths. We consider 3 cases:

1. Case "*L*," or base case, which corresponds to use the same bench lengths.
2. Case "*L*/2" in which some of the stopes (reduce their length to half). This means less dilution, but also higher backfilling costs.
3. Case "2*L*," in which some stopes double their length therefore allowing more dilution but reducing backfilling costs.

Finally all these schedules were compared in terms of economic value (NPV) and production plans.

The relevance of doing the validation step is that the actual plans are constructed manually and therefore require lots of effort to be made, making it impossible to do the analysis of the cases defined before unless these plans can be constructed automatically with UDESS.

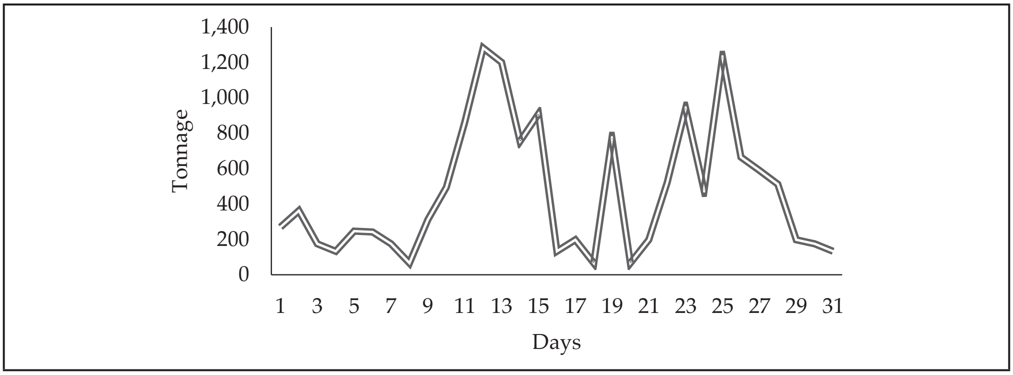

Figure 3. Reference plan constructed for the subsector used for the case study

Table 2. ELOS for stopes

Case Study	Stope Type	Wall	Width [m]	Height [m]	Length [m]	ELOS [m]	Tonnage	Total Tonnage
L	Stope Type 1	FW	2.5	16.2	15.2	0.45	257.6	515.34
		HW	2.5	16.2	15.2	0.45	257.6	
	Stope Type 2	FW	1	8.6	14.8	0.4	119.9	239.9
		HW	1	8.6	14.8	0.4	119.9	
2L	Stope Type 1	FW	2.8	16	30	0.7	791.75	1583.5
		HW	2.8	16	30	0.7	791.75	
	Stope Type 2	FW	1	8.6	30	0.5	303.97	607.95
		HW	1	8.6	30	0.5	303.97	

CASE STUDY

The case study in this paper is based on a gold deposit being exploited by the bench and fill method. We will work at the short-term horizon, looking for day to day plans for the next 31 days.

The available operational resources are: maximum construction of drifts (in meters), bench drilling, bench extraction, backfill 1 and backfill 2. Both backfills are uses at each bench, but backfill 2 is more expensive.

The reference plan constructed for the mine is displayed in Figure 3. We indeed observe that it is very irregular. This is because it corresponds only to a subsector of the whole mine.

Dilution Computation

As mentioned before, we used the concept of ELOS to compute the dilution. For this, the case "*L*/2" was considered as a reference with no dilution and then we computed the dilution for cases "*L*" and "2*L*" as reported in Table 2.

Planning Parameters

The planning parameters correspond to a specific sector of the mine. We list them in Table 3. Notice that the tonnage restriction limits the sum of bench and drift material extracted in a given period.

Table 3. Planning parameters for the case studies

Case	L/2		L		2L	
Variable/Range	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Tonnage [ton/month]	10,000	18,000	10,000	18,000	18,000	30,000
Backfill 1 [m^3/month]	5,000	7,700	5,500	7,700	1,000	8,000
Backfill 2 [m^3/month]	500	1,000	500	1,000	500	2,000
Drill meters [m/month]	3,000	5,000	3,000	5,000	500	5,000

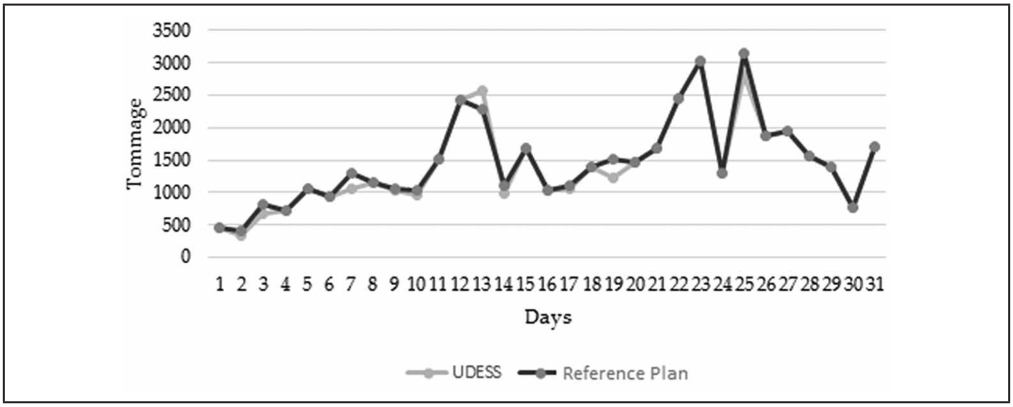

Figure 4. Reference plan, UDESS plan following reference plan, and UDESS plan for average capacity constraints

RESULTS AND ANALYSIS

Validation Instance

For the validation step in which we force UDESS to follow a reference plan, we observe that the software is able to produce schedules and production plans that comply with all the method constraints and follow a reference plan (Figure 4).

Analysis of the Impact of Dilution

What follows is a display of the production plans obtained through UDESS for each of the case studies. Variations in tonnage are observed in specific periods; this is due to the fact that available resources in these timeframes are greater, as the filling activities are complete. Given that an extraction range per period is given, these peak and valley are within established ranges.

The economical evaluation that is obtained for each of the cases is shown in Table 4.

CONCLUSIONS

We have used a computational tool, UDESS, to emulate and improve on the manual process of planning the extraction of a gold mine being exploited by bench and fill.

The tool allowed us constructing plans in a fraction of the time required for the planners and obtaining revenues for the company that are similar or higher. This means a planner could improve on the plans they currently develop, to be able to regenerate the plans in the case of changing conditions (which tends to happen often), and to make more robust decisions as they gain the ability to study different scenarios.

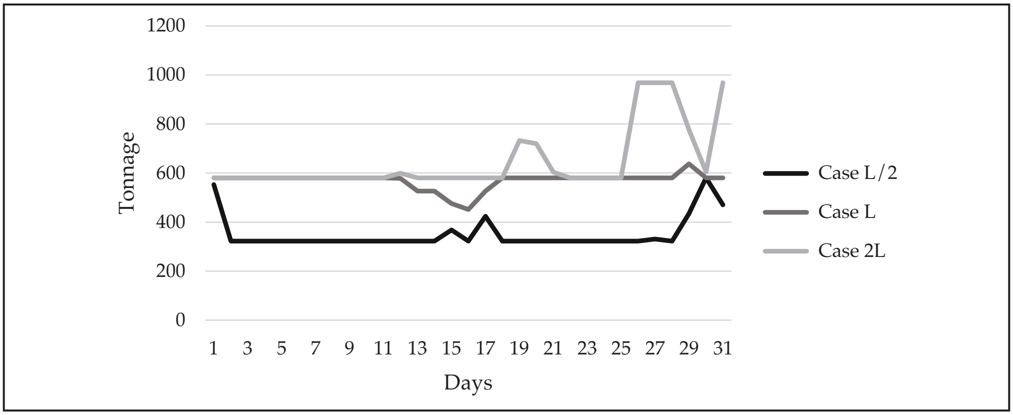

Figure 5. Production plan case L/2, production plan case L, and production plan case 2L

Table 4. NPV for each case study

Case Studies	NPV [USD]
L/2	4,769,281.17
L	7,663,318
2L	7,116,925.8

We have used this possibility to study the impact of some design parameters that impact the dilution. The result, for the small case study, show that the operation is currently at an optimum design in terms of bench length, compared to doubling or halving the length of the benches. While this is encouraging for the specific mine, having the possibility to check this and eventually optimizing over the whole mine is possible only because there is an automated tool to construct the plans.

Further research will include the extension of this application to the whole mine. This possesses the challenge to properly model the use of operational resources like equipment, because it is necessary to deal with the movement between different sectors of the mine. Other relevant issues are the study of other geomechanical considerations, like stresses; design considerations such as defining the optimum dimensions of stopes, etc.

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