Optimization of Extraction Sequence in a Bench and Fill Mine Considering the Impact of Exposure Rate on Dilution: A Case Study

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ABSTRACT

Mine planning is an iterative process, expensive in terms of time and requiring specialized engineering team. Usually, the mine planning process is sequential, that is, a production plan is completed first and then it is adapted to the mine requirements. This often results in not achieving the production goals and the lower NPV than estimated in the original plan.

The main goal of this work is to compare and quantify the impact of dilution and exposure rate of the hanging wall on the optimal mining scheduling. For this purpose, production plans have been prepared for a Bench & Fill operation using, firstly, the traditional approach of mine planning and, secondly, the integrated approach (integrating dilution and extraction rate simultaneously in the mine planning process) using real mine site data.

The operational constraints (fill movement and production rate) and the benefit of each activity was used in determining the order of the extraction sequence. The sequencing of the activities was made using the software UDESS (a software tool developed by Delphos Mine Planning Laboratory), which provided the optimal extraction sequence and a production plan for all scenarios.

While comparing the results, it was observed that incorporating dilution into the process impacts directly into the extraction sequence, which means that the order of stope extractions is different from in the original plan, the NPV is lower, and therefore the plan is different. In addition, it was shown that dilution decreases while applying the incremental exposure rate of the hanging wall.

It can be concluded that the variations in the exposure rate imply a variation in dilution, the production plan, and the extraction sequence.

INTRODUCTION

Within small and medium sized mining, selective underground methods are the most common, and unlike large scale mining, engineering levels are limited mainly by available economic resources, the complexity of tasks and execution time. It is here where we can find an opportunity to improve processes and to add value to the mining business through development and implementation of new methodologies to optimize the stages of mining value chain, like the mine planning process (Luxford, 2000).

The mine planning process is iterative and done in several stages, where production plans are being modified according to operational requirements, which implicates differences between the actual plan and what is really achieved. For example, unplanned dilution is one of the variables that modifies the production plan, adding unplanned waste to the production tonnage and modifying the mean grade (Luxford, 2000).

The main goal of this work is to compare and quantify the impact of dilution and exposure rate of the hanging wall on production plan and extraction sequence. For this purpose, production plans have been prepared for a Bench & Fill operation using, firstly, the traditional approach of mine planning and, secondly, the integrated approach including two dilution models.

The rest of the paper is organized as follows. First, the methodology applied in this work is explained. Next, in section Case Study, we present the background of the studied mine and the economic and operational parameters that were considered. Then, in section Results and Discussion, we show the main results obtained and we discuss the effect of both dilution models in the mine planning process. Finally, we present the main conclusions extracted from this study.

METHODOLOGY

The methodology applied in this work consists in the modelling of a Bench & Fill mine to obtain an optimal extraction sequence and its corresponding production plan through the software UDESS. Figure 1 shows a diagram of the methodology applied, where three models of the mine are generated and given to UDESS to find the optimal extraction sequence and production plan for each model, maximizing the objective function, that is the Net Present Value (NPV) of the mine.

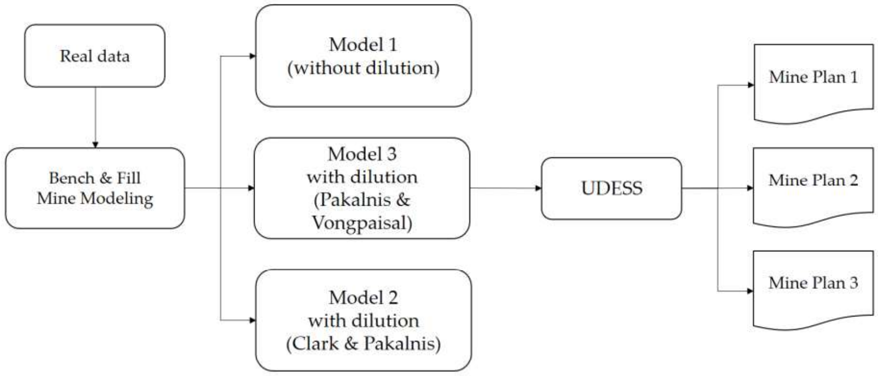

Figure 1 Methodology scheme.

UDESS (Universal Delphos Sequencer and Scheduler)

UDESS (Universal Delphos Sequencer and Scheduler) is an activity scheduler developed in Delphos Mine Planning Laboratory at Universidad de Chile. Unlike other mine planning tools, UDESS finds the optimal sequence for a several number of tasks maximizing the objective function, for instance, the Net Present Value (NPV) (Rocher, W., Rubio, E., Morales, N., 2011).

UDESS optimization is based on the concept of activities or tasks, that relates to each other through precedence constraints. Each activity has different attributes, like economic benefit and cost, and they consume operational resources to be executed. Under these considerations, UDESS generates and solves an optimization model that schedules the activities maximizing the economic benefit or minimizing the cost (Rocher, W., Rubio, E., Morales, N., 2011).

To make this possible, the software uses two text files as input: the activities file and the precedence file. These two files must be constructed by the user. The output given by UDESS is a file that contains the Gantt Chart of each activity for every period evaluated and the NPV of the model (Moreno, 2015).

Construction of the Production Plan

UDESS uses as input the activities and its precedence constraints that results from the mine model. Thus, based on a mathematical optimization model, a scheduling is generated, subject to precedence and operational constraints (Rocher, W., Rubio, E., Morales, N., 2011).

For the construction of the model, activities like horizontal development, extraction and backfill were considered. In general terms, horizontal developments must be completed so extraction may begin, while backfill act as floor for extraction of upper levels. Therefore, the number of total activities in the model is 4,105.

On the other hand, and given the extraction method conditions, five precedence groups were defined. Horizontal main developments activities correspond to all the infrastructure needed to begin the extraction, such as ramps, main drift, crosscut galleries and extraction drift. These activities must be completed to begin the extraction activity, which goes after the backfilling of the lower level. In addition, for the extraction of one level, the extraction drift of the upper level must be completed (inter level precedence). Once the extraction is concluded, backfilling may begin. According to this, the number of all precedence constraints is 9,341.

Dilution Models

For the realization of this study, two dilution models are considered and both were applied to the modelling of the stope tonnage.

The first model considered is the Clark & Pakalnis dilution model. This model considers the ELOS or Equivalent Linear Overbreak/Slough as an alternative way to represent the over excavated volume as an average depth distributed over the studied area (Castro, C., 2015. Clark, L. & Pakalnis, R.,1997).

The second model considered is the Pakalnis & Vongpaisal dilution model. This model was developed based on several observations, generating design graphs for three types of stopes (Pakalnis, R. C. & Vongpaisal, S., 1993).

CASE STUDY

The case study corresponds to an underground bench and fill mine, which its main products are gold and silver. Its total reserves are 25 [Mton] and the mean grade is 9.1 [g/ton] of equivalent gold.

Extraction Method

The mine is separated in two productive sectors, *Mine Y East* and *Mine Y West*, where each mine can be accessed independently through spiral ramps that connects each level of the mines. These ramps were design for both ways transit, for empty and loaded trucks, drillers and auxiliary equipment.

Figure 2 depicts the bench & fill method modeled in this paper as well as main location of infrastructure and mineral, from a section and plan view. In general terms, the extraction sequence is in ascending order, which means that extraction is done while lower levels are being backfilled and used as floor for the extraction of upper levels. For a given level, extraction is performed in retreat. The transversal view in Figure 2 shows the vein disposition regarding to the ramp and main drift.

For levels from 1,175 m to 1,475 m, the design considers independent ramps for east and west sectors and that main drift are constructed from the ramp every 24 vertical meters, which allows to access two consecutives levels separated by 12 vertical meters through inclined structures called pivots. For levels from 1,487 m to 1,691 m, the design considers independent ramps for east and west sectors, however the vein disposition is narrower for upper levels, so there are fewer stopes and then the number of crosscut galleries is lower.

The extraction sequence is divided in four stages, which are described following, assuming the extraction of a certain level *i*.

1. Crosscut galleries development: In order to begin the extraction drift development, the correspondent crosscut galleries must be completed. Once the crosscut gallery construction is finished, the development of the extraction drift may begin. These activities must be done in level *i* and in level *i+1*, because benching is carried out from level *i+1*.
2. Extraction drift development: As shown in Figure 3 (left), extraction drift are drilled following the vein disposition, and as a consequence waste material (grey) and ore (brown) is being extracted. In addition, the construction of the extraction drift must be completed in order to begin the benching of the stopes.
3. Extraction: The stope extraction is done through the extraction drift and in retreat. Benching is carried out in the extraction drift in level *i+1*, while the loading of broken material is carried out in the extraction drift in level *i*, as shown in Figure 3 (right).
4. Backfill: While retreat extraction proceed, the backfilling of stopes that are already extracted may begin. In this case study, the backfilling is done with waste material, as seen in Figure 3 (right).

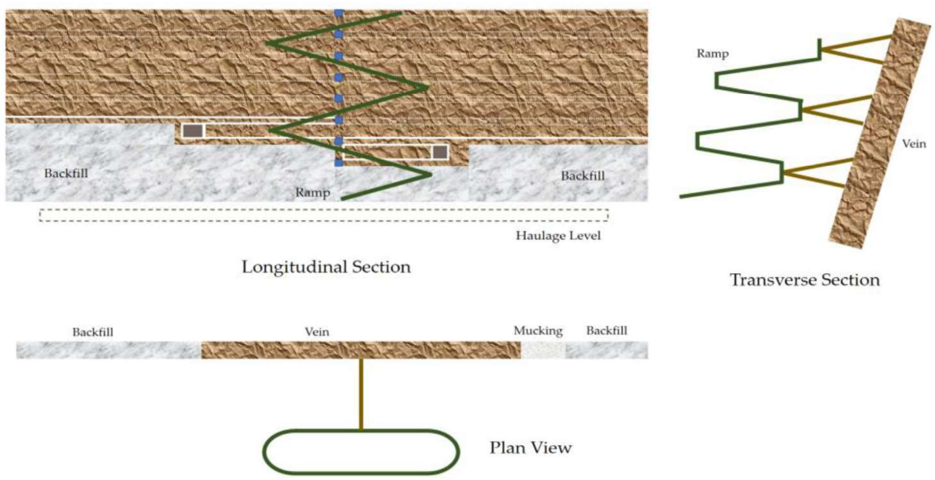

Figure 2 Bench & Fill – Mining method (Schematic Section and Plan Views).

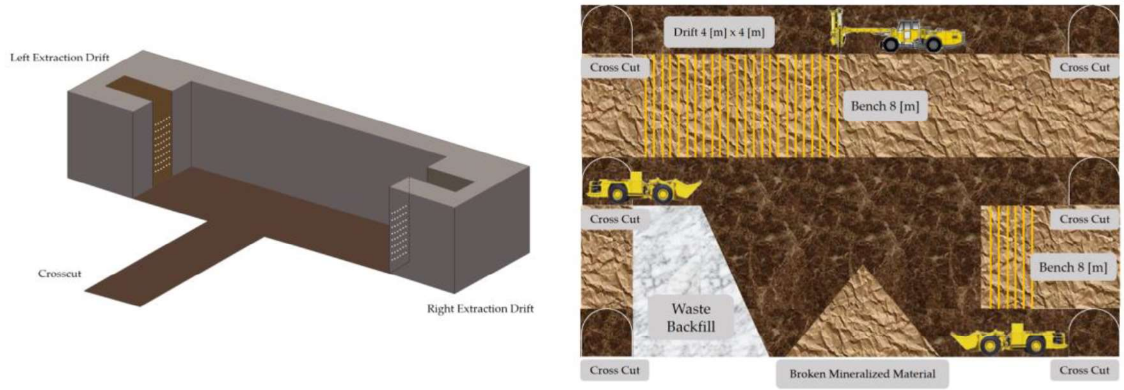

Figure 3 Bench & Fill – Split blasting (left) and sequence (right).

Economic parameters and operational considerations

For this study, a set of operational and economics considerations has been made. The extraction sequence is ascendant from level 1,175 m and from level 1,487 m, simultaneously. The waste movement rate id 645 [m^3/day] and the production rate both are 2,000 [tpd], in which 1,100 [tpd] comes from production and 900 [tpd] comes from horizontal drift developments.

Table 1 shows the economic parameters used in this study.

Table 1 Economic parameters.

Parameter	Value
Gold Price [US$/t oz]	1,190.4
Selling Cost [US$/t oz]	42.62
Metal Recovery [%]	93
Mine Cost [US$/t]	54
Processing Cost [US$/t]	34.84
G&A Cost [US$/t]	16.32
Horizontal Development Cost [US$/m]	1,100.0
Backfilling Cost [US$/t]	4.36
Discount Rate [%]	10

RESULTS AND DISCUSSION

For this case study, three different scenarios have been analyzed:

1. Mine planning without considering dilution models.
2. Mine planning considering dilution through the Clark & Pakalnis model.
3. Mine planning considering dilution through the Pakalnis & Vongpaisal model.

Production plans generated by UDESS for each scenario are shown in Figure 5, where minimal differences in the final periods can be appreciated. However, these differences are not conclusive regarding the quality of the results, for this reason the extraction sequence for each scenario must be analyzed carefully. Figure 6 shows the extraction sequence for each scenario, where scenario 2 presents the main differences regarding scenario 1: some of the stopes in the upper levels were left unextracted, while in scenario 1 and 3, all the stopes were extracted.

For making differences between scenarios clearer, Figure 6 shows a numerical scale for each stope. If the stope is blue it means that the extraction of this stope has been advanced regarding its extraction in scenario 1. On the other hand, if the stope is green it means that the extraction of this stope has been delayed regarding its extraction in scenario 1.

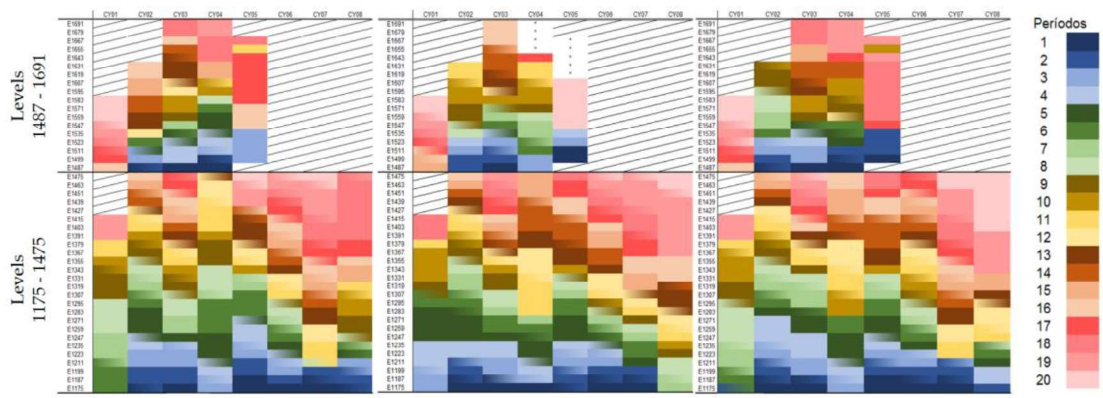

Figure 4 Section view of the extraction sequence for scenario 1 (left), scenario 2 (center) and scenario 3 (right).

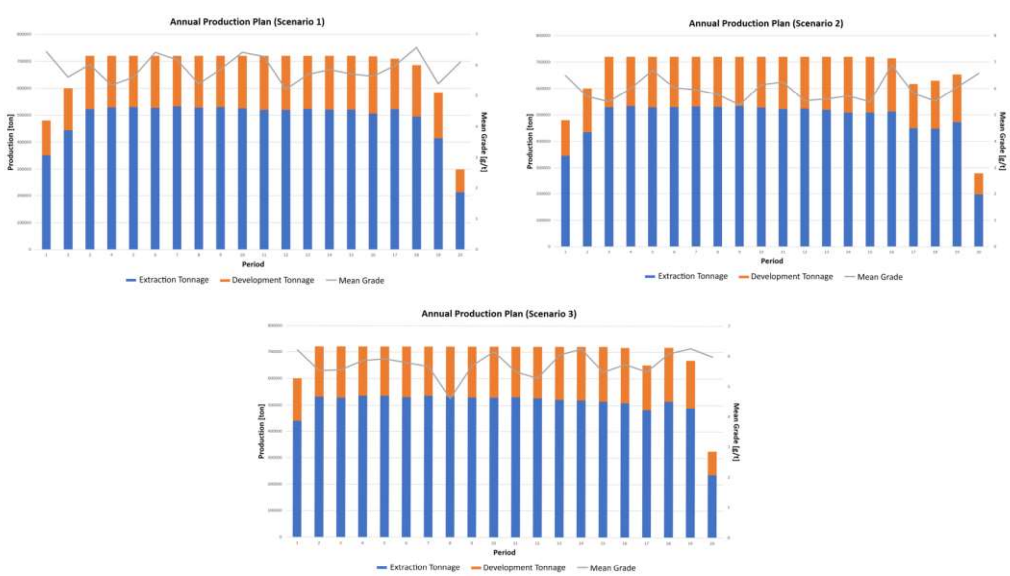

Figure 5 Annual production plan, scenario 1 (left), scenario 2 (right) and scenario 3 (middle).

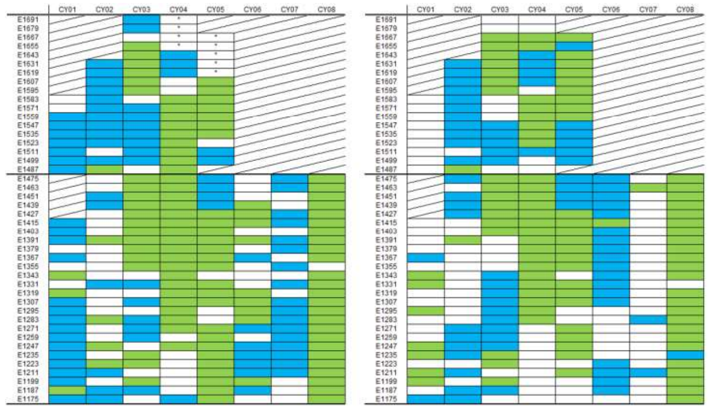

Figure 6 Section view of the extraction sequence delays for scenario 2 (left) and scenario 3 (right), with regards to scenario 1. Stopes in green are delayed with regards to scenario 1, and stopes in blue are extracted in advance to that plan.

CONCLUSION

Mine planning treated with the proper computational tools is a less complex process and takes less time to be executed. The software used in this work prove to be suitable for selective underground operations, which represents a big fraction of small and medium sized mining activity in Chile, for its use is highly recommended.

Regarding to UDESS it is possible to conclude that this tool is highly efficient, robust and easy to use. Working with models that contain more than four thousand activities and more than nine thousand constraints, the software gave results with execution time of the order of an hour, which is a brief time compared with the mining industry standards for the mine planning process.

It is possible to conclude that dilution models have an effect over the production plans and the extraction sequence that is marginally reflected on the NPV, but it allows to develop new extraction strategies based on more information and the production plans obtained is more reliable, realistic and similar to operational reality.

Finally, according to the results of the case study, it can be concluded that dilution has a direct impact on production plans, the extraction sequence and the NPV, allowing the mine planner to obtain results that are closer to the operational reality and less susceptible to changes in later stages of the mine planning process.

ACKNOWLEDGEMENTS

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