Generation of a Monthly Mining Development Plan for Underground Mines Using Mathematical Programming

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Abstract. Mine development is necessary to enable all required infrastructure to begin production in a mine sector or to give support for the productive sector. The development plan is subject to constraints, making the planification process highly time and computationally consuming. From a mathematical point of view, this is an optimization problem in which the objective function is the execution time of mine development, considering a given time horizon.

In this paper, a methodology is proposed, which allows to resolve the time optimization problem for underground mine development, minimizing the execution time and considering operational, geotechnical and deadline constraints. The case study is based on an underground mine extracted by panel caving method. A mathematical model is based on mixed integer programming in which several activities are scheduled and sequenced in a given time horizon, independent of the extraction method. The results show an executable development plan within a 12-month period fulfilling each of the restrictions raised in the problem.

The proposed methodology considerably reduces the time of the development plans allowing to consider different scenarios before the final execution plan is selected.

Keywords: Mine Planning, Underground Mining, Scheduling.

1 Introduction

Mine planning optimization is well developed and widely used in open pit mining as the mining operation progresses outwards with the deepening of the pit. Underground mining is much more complex as, throughout the life cycle of the mine, the directions of growth depend, among other factors, on the extraction method (Alford et al, 2006) and specific characteristics of the mineral deposit often requiring a unique design; therefore, creating generic optimization algorithms is more difficult (Newman et al, 2010). This complexity does not allow for the developed algorithms to be applied across all underground and, thus, a heuristic approach must be considered. The main differences between algorithms and heuristics, both considered *step-by-step procedures*, is that optimization algorithms iterate until finding an optimal solution while heuristics iteration make a trade-off between the quality of the solution and the calculation time.

According to Musingwini (2016), there are different algorithms and heuristics that are applicable to the mine planning problem, for example, the Simplex Algorithm for linear programming problems formulated by Dantzig or the Dynamic Programming algorithm used by Lerchs & Grossmann (1965) applicable in open pit mining in the determination of the final pit.

In underground Panel Caving operation, the development plans are created by expert mine planners, who use common criteria and historical data to build these plans. There are no defined methodologies that would allow to optimize the available resources and, most importantly, to analyze possible scenarios for the execution of these plans. This approach often leads to non-compliance of the development plan with the established period for the execution of the mine development. Therefore, the development of methodologies that would allow to plan more efficiently, ensuring an optimal result (or close) given the specific mine conditions would minimize the non-compliance and lead to more optimal use of the resources during the mine development stage.

In this paper, a methodology is proposed to address the time optimization problem for underground mine development, minimizing the execution time and considering operational, geotechnical and deadline constraints.

2 Methodology

2.1 UDESS - A Mathematical Programming Model

UDESS is a mathematical programming model developed at the Delphos Mine Planning Laboratory, University of Chile (Rocher, W, Rubio, E, Morales, N., 2011), where a mixed integer programming model of activity sequencing is used. The application of this model to the mine development optimization sought to minimize the execution time of the mining development plan, subject to precedence constraints between activities, operational constraints and deadline milestones of certain development activities. The outcome of this model is a Gantt chart of the activities of the development plan.

The main characteristics of the model are as follows. Let's consider a set of periods $t = \{1, ..., T\}$, a set of activities $i = \{1, ..., A\}$ that must be scheduled, $r = \{1, ..., R\}$ a set of resources that can be consumed by *starting*, *ending* and *development* of each activity i, and that have certain availability in each period t. Each activity i has a cost/benefit v_i associated with its development, and v_{i+} and v_{i-} associated to its start and end, with a minimum and maximum rate (v^i_{min}, v^i_{max}) that limits the progress of each activity during each period t. Finally, each activity i has associated a set of predecessor activities given by $P(i)$.

The decision variables of this model are:

- p_{it}: Percentage of progress of activity i in period t (continuous variable whose value is p_{it} = [0,1]).
- s_{it}, e_{it}: Start and end variables, respectively, for activity i (binary variable, whose value is 1 if activity i starts/ends in period t or before, 0 otherwise).
- k_{iPt}: Variable that establishes relations of precedence between the successor activity i and a group of preceding activities $P \epsilon P(i)$ (binary variable, whose value is 1 if all the activities of the group $P \subseteq P(i)$ are completed in period t, 0 otherwise).
- τ_{it}: Time consumed by activity i in period t and its predecessors.

The set of main constraints is given by:

- Operational resource constraint: Each activity can consume $\lambda_{i,r}$ amount of a resource r during its development. This constraint limits the resources consumed in each period (given by $R^r_{min,t}$, $R^r_{max,t}$ respectively) for all activities.
- Progress limit constraint: It is possible to require for each activity i a minimum or maximum rate of progress in period t (limits given by b-i, t, b + i, t respectively).
- Range resource constraint: Activities are required to have a minimum (R_{rm}) and maximum (R_{rM}) consumption of a resource r during a certain time interval ([t^r_{min}, t^r_{max}]).
- Starting resource capacity constraint: It is possible to model that activities consume a resource r when initiating or finishing their progress (given by λ_{+ir} and λ_{-ir}, respectively), which must be in a certain range given by [$S^r_{min,t}$, $S^r_{max,t}$] for the beginning, and [$E^r_{min,t}$, $E^r_{max,t}$] for the end of the activity.
- Activity incompatibility constraint: It is possible to model that a certain set of activities cannot start during a certain time interval.
- Starting period constraint: It is possible to force the start of a set of activities C between certain interval given by [t^C_{min}, t^C_{max}].
- Precedencies: Each activity i has a set of precedencies $P(i)$ that can be divided into groups $P \subseteq P(i)$. Precedencies can be generated as type *"and"*, in which all groups of the set $P(i)$ must be completed before starting activity i, or as type *"or"*, where it is required that at least one of the groups $P \subseteq P(i)$ must be completed to start activity i.

2.2 Mine Development Optimization Methodology

The proposed methodology takes the mine development plan (prepared by the experts of the mine operation) as a base plan or input to the UDESS model. The base plan consists of various activities, such as horizontal and vertical developments, infrastructure construction and installation subject to various constraints, precedencies and milestones.

The activities are discretized to avoid unique advance face if the activities are extensive in development. The activities are related to each other by precedencies constraints (see Section 2.1), which determine the order in which each activity is executed and have different attributes and consume different types of resources. The constraints of the case study, including operational, deadline and resource consumption constraints, are identified before the optimization heuristics is applied to solve the optimization problem to find an optimal scheduling of activities and the associated Gantt Chart.

3 Case Study

The methodology was applied in an underground operation located in Chile. The operation had nine underground Panel Caving mines and one open-pit mine, which together represented an average annual production of 142,000 tpd.

The mine had four productive sectors, of which only one was considered, and four levels: sinking, production, ventilation and hauling, where trains were used as a transport system for ore to the surface.

3.1 Construction Sequence of the Mine

Construction sequence of the extraction method was considered in modeling of the mine development plan. Fig. 1 shows the construction sequence of the mine considering four levels: undercut, production, ventilation and haulage as well as the ore pass systems.

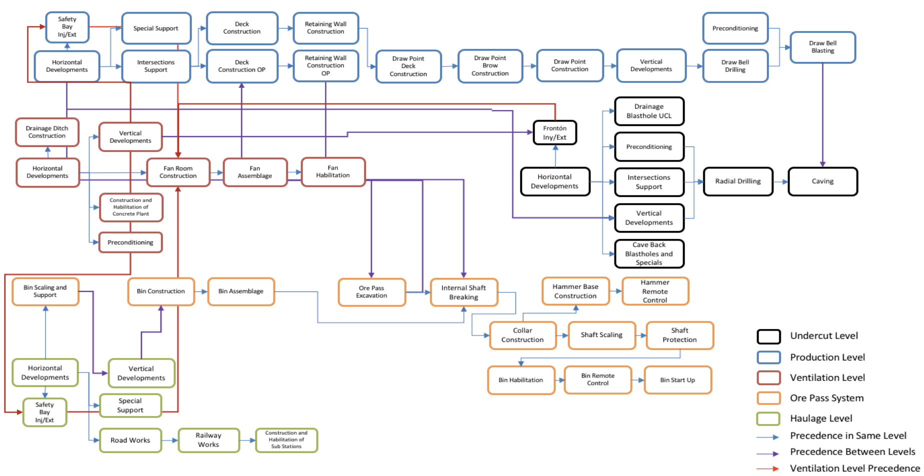

Fig. 1. Construction sequence of a conventional Panel Caving mine.

3.2 Mine Development Plan

To fulfill the production goals, both in projects currently in execution and in future projects, a proper planning of mining development must be carried out for different time horizons.

The long-term plan had a time horizon ranging from six to fifty years and, in relation to mine development, it provided global figures required to comply with the production plans.

The medium-term plan had a time horizon of one to five years. This delivered the annual volumes of works required to comply with the production plans.

The short-term plan had a time horizon of 1-year and its main function was to deliver the volumes of works considered during the annual period in the budgets allocated for the mining development.

The monthly short-term plan had a time horizon of 1-year and provided the growth guidelines for each sector and the monthly requirements for the incorporation of the area as well as incorporation of all the milestones of mining development to assure sustainability and continuity of production. It indicated when some of the main milestones had to be developed; the details of the activities to be developed monthly were added afterwards.

4 Results

4.1 Mine Modeling

Table 1 shows the main outcomes of the implementation of the mine development plan within the optimization model.

Table 1. Main results of the mine modeling with mathematical programming.

Level	Activities	Precedencies	Constraints
Undercut Level	210	417	409
Production Level	775	1,489	812
Ore pass Systems	153	258	39
Haulage Level	140	232	64
Ventilation Level	162	286	68
Total	**1,440**	**2,682**	**1,392**

The development of the activities and their precedence relationships can be modeled as precedencies of the "and" type and the "or" type. Of a total of 2,682 precedencies, 1,834 correspond to precedencies of the "and" type, while 848 correspond to precedencies of the "or" type.

4.2 Main Activities

Most of the activities focused on sinking and production levels, thus, the most relevant results for these levels are shown providing a good representation of the outcome for the rest of the mine. The activity with most volume of work in both levels corresponds to horizontal developments and, as shown in Fig. 2, the mathematical model is able to schedule all the plan activities leaving a small volume of activities to be carried out towards the final periods. The results for the rest of the activities in all levels are analogous, that is, all the activities of the development plan are scheduled within the 12-month horizon, respecting all constraints and leaving more time available towards the final periods.

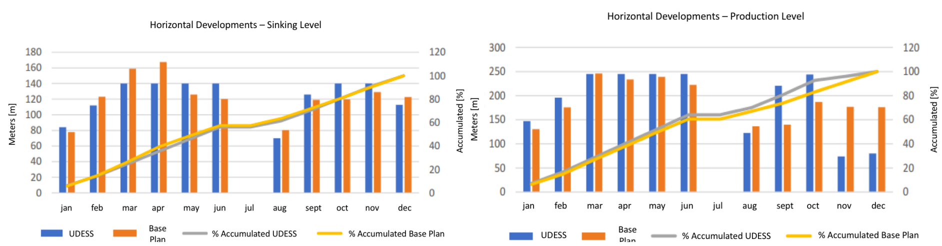

Fig. 2. Horizontal developments for undercut and production levels for the base development plan and the UDESS development plan.

5 Analysis

5.1 Modeling

The original activities presented in the development plan were taken and a discretization of these was carried out. For example, considering an activity of horizontal development of 100 meters, this activity was discretized or divided into 5 smaller activities of 20 meters each. The discretization for the modeling was made based on the discretization used by the expert planners of the operation for the construction of the plan, which complied with the operational requirements of the mine.

The advantage of the methodology applied to this case study was that most of the commercial scheduling software only use "and" type precedencies, thus the generated plans are more rigid in terms of possible outcomes. The mathematical model provides greater flexibility to the activity scheduling by incorporating type “or” precedencies, allowing the generation of plans that are closer to the operational reality.

5.2 Base Development Plan v. UDESS Development Plan

The model scheduled all the activities associated with the program for the 12-month period (January to December 2017), which corresponds to the time horizon of the program.

The results obtained in scheduling the activities vary with respect to the original program, in many cases leading to important differences in sequencing and scheduling.

This is mainly explained by analyzing the objective function that UDESS is using, which minimizes the total execution time of the plan, therefore, whenever possible, the software tries to advance the development works.

5.3 Milestones

In addition to being operationally feasible, the development plan must comply with a series of milestones in each level of the mine. The schedule given by UDESS fulfills all the milestones required, as shown in Table 2. When comparing both plans, it can be observed that the original plan does not meet the required deadlines established for three of the milestones required, which results in 84% compliance.

Table 2. Comparison between base plan fulfillment and UDESS plan fulfillment.

Milestone	Deadline	Fulfillment Base Plan	Fulfillment UDESS Plan
Finishing special gallery south of crosscut access 4 at UCL	February	✓	✓
Connection ditch-53/crosscut-45at PL	February	✓	✓
Finishing special hydrocracking at PL	February	✓	✓
Finishing wall construction between ditches 49 and 50 at PL	February	✓	✓
Crosscuts 25 and 27 connections at UCL	March	✓	✓
Crosscut access 6-ramp connection al UCL	March	✗	✓
Total connection ditch-54/crosscut-27 to 59 at PL	April	✓	✓
Finishing special fortification at IZ	April	✗	✓
Enabling electrical station in crosscut-46 at VL	April	✓	✓
Finishing special fortification at Hw PL	May	✓	✓
Finishing constructions in crosscut-51 to 53 at north of ditch-49 PL	June	✓	✓
Total enabling injection crosscut-41 at VL	June	✗	✓
Enabling crosscut-38 at Block 1	June	✓	✓
Total fortification of crosscut-54 at PL	July	✓	✓
Connection ditch-54/crosscut-63/crosscut-1 at PL	August	✓	✓
Total enabling of extraction crosscut-46 at VL	December	✓	✓
Total enabling of crosscut-38	December	✓	✓
Finishing bin assembly in crosscut-43 at HL	December	✓	✓
Finishing labors inside shaft in crosscut-43 at PL	Various	✓	✓

5.4 Sensitivity Analysis

A sensitivity analysis was carried out, considering the scheduling of the mining development plan activities considering advancing the activities by 1-month. Those activities in which the rescheduling was possible, a new reschedule to advance the activities by two months was tested.

The results indicate that 57% of the activities of the plan accept the 1-month rescheduling. Of this 57% only 3% of activities can be scheduled two months beforehand, as shown in Fig. 3. This result indicates that the plan has a good degree of flexibility to carry out the scheduling of activities, considering the multiple constraints of the problem.

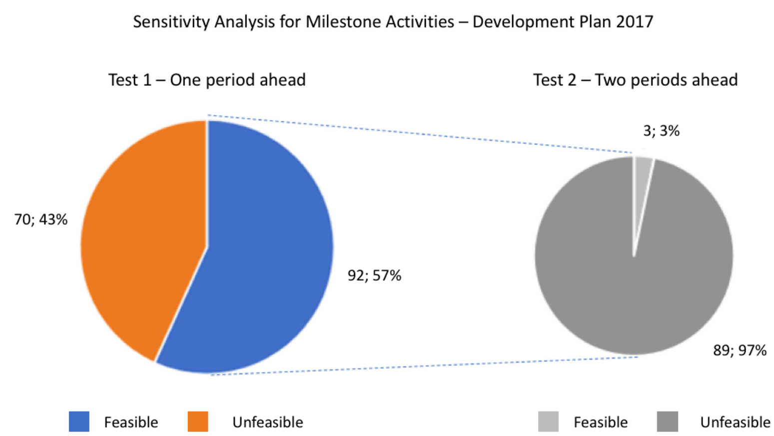

Fig. 3. Sensitivity analysis results for milestones and activities.

6 Conclusions

The comparison of development plans created by experts and using new methodology identified multiple improvement opportunities. It was possible to reassign or add more activities in certain periods, where a large number of activities was not being developed, redistributing the available resources for greater efficiency or reducing the number of resources used.

Both plans scheduled all the activities within the established maximum period of one year (12 months), however, the due dates for milestones were not the same. While the expert schedule complied with 84% of the established due dates, the development plan built in UDESS complied with 100% of them.

The ability to model precedencies, such as type "and" and type "or", allowed the optimization model greater flexibility and, therefore, brought the results closer to the reality of the mine operation.

The results obtained from the sensitivity analysis established that there were improvement opportunities in scheduling, since the original plan had certain gaps that had not been considered. In addition, UDESS provided the capacity and flexibility to test various development scenarios, a capacity that is nonexistent at present time due to the way in which the programs are built by the experts.

It was shown that an effective modeling methodology was created and validated in a real-case scenario adding value to the process of mine planning.

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