Optimization of an Annual Mining Development Plan Using Mathematical Programming

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ABSTRACT

The main objective of mine development planning is to provide the required infrastructure to ensure production in short and medium term. Currently, there is not a well-established methodology to elaborate mine development plans, which means that this process is subject mainly to the expert's criteria and the results are not necessarily optimal.

From a mathematical perspective, this may be approached as an optimization problem, where an optimal sequence of execution of the plan is sought within a certain time horizon. However, solving an optimization problem of this kind is highly time and resource consuming.

The aim of this work is to propose a methodology to obtain the best mining development plan through mathematical programming, minimizing the execution time in a given time horizon, and considering operational, geotechnical and deadline constraints.

The case study is the 2017 mining development plan of a Panel Caving operation. As this plan has already been executed, the idea is to compare the compliance between the original and the generated plan. To solve this problem, a mathematical model based on mixed integer programming is applied, in which the activities are scheduled and sequenced in a 12-month time horizon.

The result shows an executable mine development plan, fulfilling each of the constraints raised in the problem. These results were validated by the engineering team of the mine. Even though both plans schedule all the activities within the established time horizon, the compliance for the defined milestones in the original plan is 84 %, while the mathematical model generated plan complies with 100 % of the milestones.

In conclusion, the proposed methodology is effective and validated with a real case. Additionally, allows to considerably reduce the elaboration time for mine development plans, allowing to gain analysis time considering different scenarios before its execution, adding value to the planning process.

INTRODUCTION

Mining development is the set of all activities necessary to enable infrastructure to sustain the exploitation of a productive sector, and just as production must be planned, mining development must be carefully planned as well in order not to delay mining production or interfere with production activities (Camhi, J., 2012).

The mine development plans are created by expert mine planners, who use common criteria and historical data to build these plans. Nevertheless, here 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 within 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.

The optimization of mine production planning has been widely addressed by various authors, both in open pit and underground mining (Newman, A. M., Rubio, E., Caro, R., Weintraub, A., & Eurek, K., 2010), nevertheless, in underground mining this is a more complex task, and one that is currently supported by a fairly small amount of research. This complexity means that in many cases the resolution algorithms cannot be applied, so they must be solved using a heuristic approach (Alford C., Brazil M., Lee D.H., 2007). Despite being a crucial issue, the optimization related to mine development plans has not received enough attention to generate methodologies that help improve the process.

From a mathematical programming point of view, the planning of mining development can be seen as an activity schedule problem, where activities are related to each other by precedencies, and subject to a series of constraints that can be operational, geotechnical, milestones or deadlines. In this context, activities are all tasks of the plan that must be executed, precedencies establish the order in which these activities must be executed, and constraints establish conditions that must be met to find the solution.

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, milestones and deadline constraints.

METHODOLOGY

The proposed methodology takes the mine development plan as a base plan or input to run a mathematical optimization model that will generate an optimized version of this plan. The base plan consists of activities, such as horizontal and vertical developments, infrastructure construction and installation, related between each other through precedencies, subject to operational constraints, due dates and milestones. These activities, precedencies and constraints are the inputs for the mathematical optimization model and, once entered, the model finds an optimal scheduling and sequence in Gantt Chart format, as can be seen in Fig. 1.Finally, a comparative analysis can be done between the base plan and the plan obtained through the mathematical model.

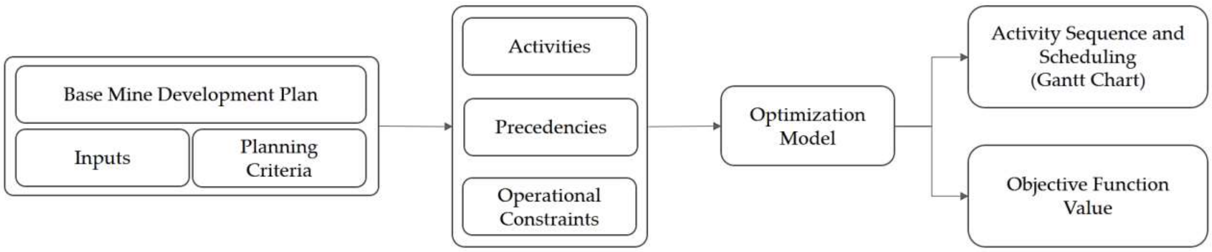

Figure 1 Summary of the proposed methodology

UDESS – A Mathematical Programming Model

UDESS is a mathematical mixed integer programming model developed at the Delphos Mine Planning Lab, University of Chile, that allows to sequence a given set of activities, related to each other through precedencies and subject to different kind of constraints, optimizing an objective function. The outcome of this model is the sequence presented as a Gantt chart of the activities and the optimal value of the objective function. The optimization model is the following:

$$\max \sum_{t\in\tau}\sum_{i\in A} b(i,t)p_{it} - c^{+}(i,t)(s_{it} - s_{i,t-1}) - c^{-}(i,t)(e_{it} - e_{i,t-1}) \quad (1)$$

$$s_{it} \geq s_{i,t-1} \qquad (\forall i \in A)(\forall t \in \tau) \quad (2)$$

$$e_{it} \geq e_{i,t-1} \qquad (\forall i \in A)(\forall t \in \tau) \quad (3)$$

$$p_{it} \leq s_{it} \qquad (\forall i \in A)(\forall t \in \tau) \quad (4)$$

$$e_{it} \leq \sum_{t'\leq t} p_{it'} \qquad (\forall i \in A)(\forall t \in \tau) \quad (5)$$

$$p_{it} \leq \bar{v}(i) \qquad (\forall i \in A)(\forall t \in \tau) \quad (6)$$

$$\underline{v}(i)(s_{it} - e_{it}) \leq p_{it} \qquad (\forall i \in A)(\forall t \in \tau) \quad (7)$$

$$\sum_{i\in A} w(i,r)p_{it} \leq W(r,t) \qquad (\forall r \in R)(\forall t \in \tau) \quad (8)$$

$$g_{Gt} \leq e_{jt} \qquad (\forall i \in A)(\forall t \in \tau)(\forall G \in G_i)(\forall j \in G) \quad (9)$$

$$s_{it} \leq \sum_{G\in G_i} g_{Gt} \qquad (\forall i \in A)(\forall t \in \tau) \quad (10)$$

$$\phi_{it} \leq L(t) \qquad (\forall i \in A)(\forall t \in \tau) \quad (11)$$

$$M(1 - g_{Gt}) + \phi_{it} \geq \phi_{jt} + \ell(i)p_{it} \qquad (\forall i \in A - S)(\forall t \in \tau)(\forall j \in \cup_{G\in G_i} G) \quad (12)$$

$$\phi_{it}, p_{it} \geq 0 \qquad (\forall i \in A)(\forall t \in \tau) \quad (13)$$

$$s_{it}, e_{it} \in \{0,1\} \qquad (\forall i \in A)(\forall t \in \tau) \quad (14)$$

$$g_{G,t} \in \{0,1\} \qquad (\forall i \in A)(\forall t \in \tau)(\forall G \in G_i) \quad (15)$$

Where i, j and A are activities and set of all activities; t y τ are a time period and the set of all periods; $L(t)$ is the length of period t (in a fixed time unit, e.g. months); $c^{+}(i,t)$ c+(i,t) and $c^{-}(i,t)$ are the cost of starting and ending activity i at period t; $b(i,t)$ is the net profit of performing activity i at a period t; G_i is the collection of precedence groups of i; $G, G_{ik} \in G_i$ is a precedence group of activity i; r and R are resources and the set of resources; $w(r,i)$ is the resource usage of r for total execution of i; $W(r,t)$ is the total availability of resource r for period t; $\overline{v}(i)$ and $\underline{v}(i)$ are the minimal and maximal rate of execution of i (in percentage of time); $\ell(i) = 1/\overline{v}(i)$ is the duration of i if executes at maximal rate (in same units as $L(t)$) and S is the set of root activities.

Variables s_{it} and e_{it} control the starting and ending of activities to control precedences. x_{it} corresponds to the percentage of progress of an activity. The goal function (1) considers costs/benefits for starting, ending or advancing the activities. Constraints (2) - (5) define the variables, (6) and (7) are maximum and minimum rate constraints, (8) are the resources availability constraints. (9) and (10) are the precedence constraints. Finally, (11) - (12) are the time utilization of activities within the scheduling time slots (Rocher, W, Rubio, E, Morales, N., 2011).

This mathematical model support two different kind of precedencies: type "and" and type "or". The type "and" precedencies are those in which all the predecessor activities must be completed to begin to develop the successor activity. As seen in Fig. 2, activities a_1, a_2 and a_3 must be completed in order to continue with activity a_i. On the other hand, type "or" precedencies are those in which at least one of the predecessor activities must be completed in order to begin the development of the successor activity. As seen in Fig. 2, it is enough to complete one out of three predecessor activities (a_1, a_2 or a_3) in order to continue with activity a_i.

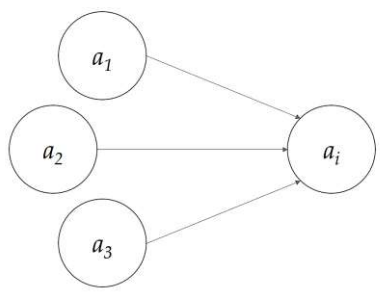

Figure 2 Diagram representing precedencies between activities.

CASE STUDY

The methodology was applied using the mining development plan of a mining operation located in Chile and considering the four typical levels of a Panel Caving operation: sinking, production, ventilation and hauling, in addition to the ore pass systems.

To implement the base plan into the mathematical model, 1,440 activities, 2,682 precedencies and 1,392 restrictions were defined. Of a total of 2,682 precedencies, 1,834 correspond to type "and" precedencies, and 848 correspond to type "or" precedencies.

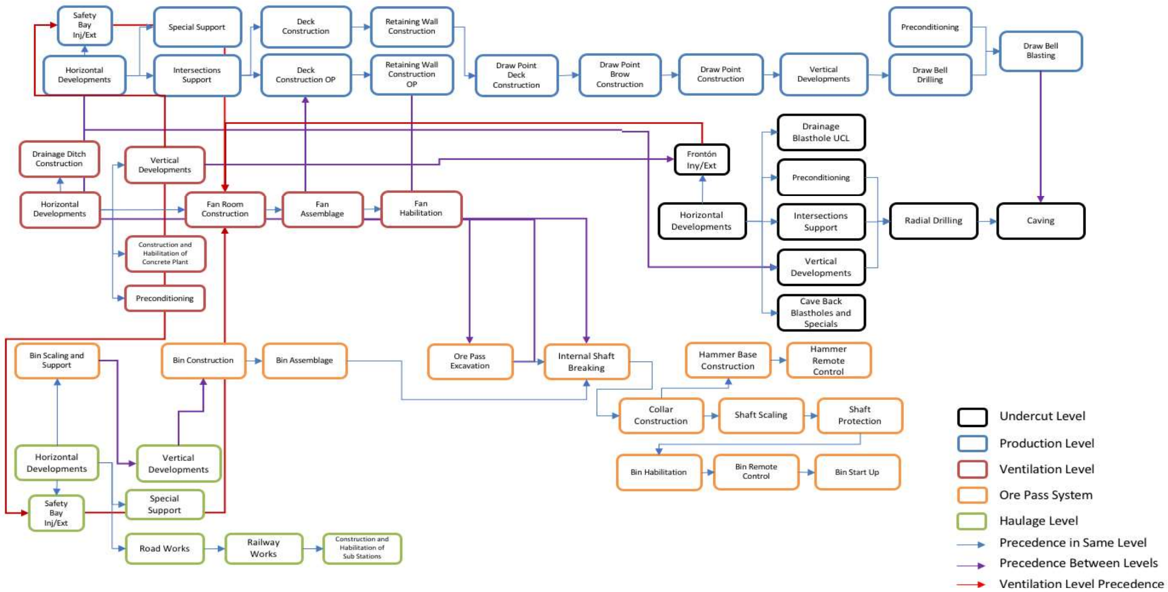

Figure 3 Construction sequence of a conventional Panel Caving mine.

Mine Development Plan (Base Plan)

The base plan used in this case study is a monthly short-term plan with a time horizon of 1 year and its aim is to deliver the volumes of works considered during the annual period, and 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 also indicates when some of the main milestones had to be developed; the details of the activities to be developed monthly are added afterwards.

Constraints, Milestones and Deadlines

In addition to being operationally feasible, the development plan must comply with a series of constraints, milestones and deadlines in each level of the mine. A very important constraint is that in July no work can be done due to a contractor change. Milestones are works executed by other divisions of the company, which must be ready by a certain date in order to continue with the execution of the mining development works. Deadlines are certain development activities which must be completed by a certain date in order to continue with the mine development plan.

Construction Sequence of the Mine

In order to establish the precedencies between activities, it is necessary to know the constructive sequence of the mine, in this case, of a conventional Panel Caving.

First of all, the precedencies of the activities of each level were established separately, to then establish precedencies between levels. The construction sequence, considering all the levels of a Panel Caving operation, can be observed in Fig. 3.

RESULTS AND ANALYSIS

Main Activities

Most of the activities are developed in undercut 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. 4, 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.

Figure 4 Horizontal developments for undercut and production levels for the base development plan and the UDESS development plan.

Figure 5 Horizontal developments for haulage and ventilation levels for the base development plan and the UDESS development plan.

Figure 6 Bin construction and shaft protection in ore pass system for the base development plan and the UDESS development plan.

Table 1 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	✓	✓

Base Development Plan vs. 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.

In the horizontal developments plan in undercut and production levels, in Fig.4, a similar distribution of jobs is observed along the time horizon, which does not occur in the plans of haulage and ventilations levels, as seen in Fig.5. This can be explained through the use of historical data for performance in the elaboration of the development plans, and in the case of the haulage and ventilation levels, these values may be very high. It may also be due to the availability of resources by level, giving priority to higher impact works such as ore pass systems.

In the base plan, the works of the ore pass systems are scheduled for the second semester, while the plan generated by UDESS tends to do this works in advance, towards the first semester, as seen in Fig.6. This can be explained by two reasons: because a large part of the activities of the ore pass systems do not have any precedencies or because these activities are not limited in terms of resources.

Several civil works were scheduled before regarding the base plan scheduling, and as a consequence there is available time to perform additional activities in the final months of the time horizon, so it would be interesting to evaluate the possibility of incorporating more activities into the plan to use this available time.

The schedule given by UDESS fulfills all the milestones required (100% compliance), as shown in Table 1. When comparing both plans, it can be observed that the base plan does not meet the required deadlines established for 3 out of 19 required milestones, which results in 84% compliance.

CONCLUSION

The proposed methodology allows the automation of the mine development planning process, generating equivalent solutions that are operationally feasible. In general terms, the mathematical optimization model generates redistributed plans in comparison with the original plan, bringing forward some activities when priority and resources allow it.

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 main advantage of the proposed methodology is the speed of generation of plans, which allows to gain time of analysis of possible scenarios, sensitivity analysis, recalculating plans during its execution, obtaining solutions of higher resolution, for example, in scale of weeks or days and to consider variability in the execution times of the activities. These last two options are being explored for use in the operation of the case study.

Most of the commercial scheduling software only use "and" type precedencies, thus the generated plans are more rigid in terms of possible outcomes. Other advantage of the methodology applied to this case study is that 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.

These results indicate that there are improvement opportunities in mine development scheduling, since the original plan had certain gaps that had not been considered. In addition, UDESS provide the capacity and the flexibility to test various development scenarios, a capacity that is non-existent 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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