An application of Direct Block Scheduling for short-term construction scheduling in panel caving

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Abstract

Mine preparation is an important aspect of underground mining with an enormous impact on the availability of infrastructure for production and, therefore, on the economic value of a project, its execution, and the safety of the operation. Mine preparation involves several areas of operation from mine planning to geomechanics, supply, Human Resources, among many others. Despite the relevance of mine planning, optimization tools to support this process are lacking, both in practice and in the literature. This leaves the planner with few opportunities to test the robustness of construction plans, which may impact their fulfillment and, therefore, the whole project. In this work, an optimization methodology is proposed to evaluate different sequences of mine construction occurring simultaneously at different levels of a panel caving mine in the context of a short-term plan (2 months) on an hourly basis. The methodology relies on Direct Block Scheduling, a technique that comes from mine planning in open pit mines, which is adapted here to the case of underground mine preparation. Using this method, different types of construction sequences, precedence among building activities, and different performance scenarios that depend on the characteristics of the rock mass can be analyzed. When applied to a real mine case, the results show that the plan obtained complies with all the operational constraints and, therefore, appears as a valid methodology to generate optimized plans in an automatic way and could be used by planners to evaluate different options before deciding on the best final plan.

1 Introduction

Mine development is the union of all activities necessary for constant and safe exploitation of a specific sector or mine. The development plan impacts the execution of a whole project because the availability of the production area depends on its successful execution. Historically, efforts to develop computational tools have focused on assisting the process of production scheduling and, as a result, mathematical models and optimization software to support this process, particularly in open pit mining, are widely available. In the case of panel caving, for example, there are well established software solutions to aid the determination of the optimal floor, economic envelope, and the long-term plan.

Conversely for production scheduling, construction planners do not have sophisticated models or algorithms to achieve optimal plans or test their robustness. Indeed, the process of planning mine development is more dependent on the expertise of the planner rather than on the use of optimization tools. Typically, the software used is to evaluate the plans conceived by the planners, but not to assist them in elaborating the best one.

The situation above is particularly true in the case of medium and short-term planning for underground mines. In fact, the methodology used varies from site to site, or expert to expert, and currently there is no common methodology that covers all the variables and criteria required for an optimal construction plan. Instead, sophisticated spreadsheets for the scheduling of construction activities are the most common tools for the task. The currently used approach does allow planners to find feasible solutions but leaves no space for optimization, let alone for testing the robustness of their plans or determining the long-term impact of short-term decisions.

From the point of view of mathematical programming, mining-development planning can be seen as a schedule of activities, where these activities are related through a series of restrictions that can be operational or geotechnical. They can include milestones or deadlines and require some resources for their execution, which can be shared or specialized. For example, (Kuchta et al. 2004) used mixed integer programming to schedule operations at the Kiruna Mine, specifically, which production blocks to mine and when to minimize deviations from planned monthly production quantities and comply with operational constraints. Another example is in "Block Cave Production Scheduling Optimization Using Mathematical Programming" (Pourrahimian et al. 2012), which presents an Mixed-integer linear programming (MILP) model that seeks to optimize extraction to maximize the net present value (NPV) using operational restrictions and penalties for mixing ores of different qualities. However, the maximum NPV does not consider such variables as uncertainties in grade, type of advancement, or geomechanic parameters. Finally, Nancel-Penard et al. (2020) developed an optimization model and a resolution algorithm for long-term scheduling in a panel caving mine. For a more detailed review of optimization techniques for mine planning, please refer to Cullenbine et al. (2011).

The approaches mentioned above use models that address a specific case study or at least the specific mining method being considered and, therefore, when utilizing mathematical programming, require the development of specific resolution algorithms to find good solutions. These solutions may not be applicable in a short-term context, where the number of activities and the variables on which they depend imply long periods of calculation time to be solved.

In this paper, we utilize a different approach, which consists of adapting an approach utilized for open pit mining, namely Direct Block Scheduling (DBS). In this framework, focused on production scheduling, the mathematical model decides the optimum period of extraction and destination (process or waste) for the blocks of an open pit mine, subject to precedence constraints which model the slope angles and resource constraints, such as production or mining capacity. The motivation to use DBS comes from the fact that it has been widely studied in the literature and there are efficient algorithms even when a large number of activities and variables need to be managed. See for example Espinoza et al. (2013); Lambert et al. (2014) or Jélvez et al. (2016) regarding DBS. Therefore, the approach in this work is to model construction activities as blocks and to use the computational machinery already in place through DBS to find optimal solutions.

It is worth noting that DBS has already been used in underground mining. For example, Brickey (2015) uses DBS to maximize the time-off ounces of gold extracted and determines the optimal or almost optimal sequence of development-related activities, extraction and filling of an underground mine. Constraints include physical precedence and resource capabilities. Research uses data from an existing underground mine; however, the formulation of the model has the ability to serve other underground mines in a similar way with structured data and provides the ability to customize constraints. In recent years the DBS methodology has been implemented in underground mining with different variants, but none of these have applied it to short-term (or very short-term) planning or with new restrictions.

2 Methodology and mathematical model

The proposed methodology takes the long-term mine development plan as an input for a mathematical optimization model that will generate an optimized version of this plan in the short-term. The base plan consists of activities such as horizontal and vertical developments, construction and installation of infrastructure, which are related to each other through precedents and are subject to operational constraints.

As mentioned before, we will model the construction activities as blocks (for direct block scheduling). This requires a proper discretization of the different activities, their precedences, and the resources they may require for execution.

2.1 Model considerations

For short-term planning, the model is subject to the following variables:

F.O:

$x \in X$ Activity blocks

$t \in T$ time periods defining the time horizon

$r \in R$ production and processing resources

Bb blocks above b that must be extracted directly before b

Vxt net present value of block b if extracted in period t ($)

R_{xT} consumption of resource r associated with the extraction of block b

RT_t amount of resource r available in time period t

Rm_t minimum level of resource r to be consumed in time period t

D activity precedence number

W is the time index (running from 1 to the time horizon)

$$\mathrm{MAX: VALOR} = \sum_{t=1}^{T} \mathrm{TD}^{a} \sum_{x\ e\ X} B_{xt} V_{xt}$$

- TD^a = Discount rate is given by the following formula
- $$TD = \frac{1}{(1+a)^{\frac{1}{730}}}$$

$$a = \sum_{s \le t} Ks$$ .is the accumulated time until the period t.

where Ks is the duration in shifts of the total number of activities carried out

1) $B_{xt} = \begin{cases} 1\text{ , If activity i is carried out in period t} \\ \quad 0,\ \text{in another case} \end{cases}$
2) $B_{xt} \le B_{xt}\, , \forall x \in X, t \in T$
3) $B_{xt} \le \sum_t B_{xt}\, , \forall x \in X, t \in T$
4) $B_{x,t\text{-}1} \le Bxt \ \ \forall x \in X, t > 1$
5) $\sum_{x \in X} R_{xr} \left(B_{xt} - B_{xt\text{-}1}\right) \le RT_t \ \ \forall r \in R, t \in T, x \in X$
6) $\sum_{x \in X} R_{xr} \left(B_{xt} - B_{xt\text{-}1}\right) \ge Rm_t \ \ \forall r \in R, t \in T, x \in X$
7) $B_{x,t,D\text{-}1} \le B_{j,t\text{-}\Delta,D\text{-}1} \ \ \forall x \in X, \forall w = \Delta + 1, \Delta 2, \ldots..T, \forall\ x \in X$

   $B_{x,\Delta,D\text{-}1} = 0$

2.1.1 Long-term plan

The base plan or long-term plan is a monthly plan with a 1-year horizon. This plan delivers volumes, meters and units of the work considered to be carried out on a monthly basis (horizontal, vertical, civil etc.) in an annual period. It includes the growth patterns for each sector and the monthly requirements for incorporating more area. It also indicates the most important activities that should be performed within the selected periods or to achieve the milestones. From this plan, two periods are extracted, which will be used as a base plan (horizontal developments, vertical developments, final infrastructure (roadways, etc), precedence, restrictions, etc. carried out in this period) and will be compared to the results of the proposed model.

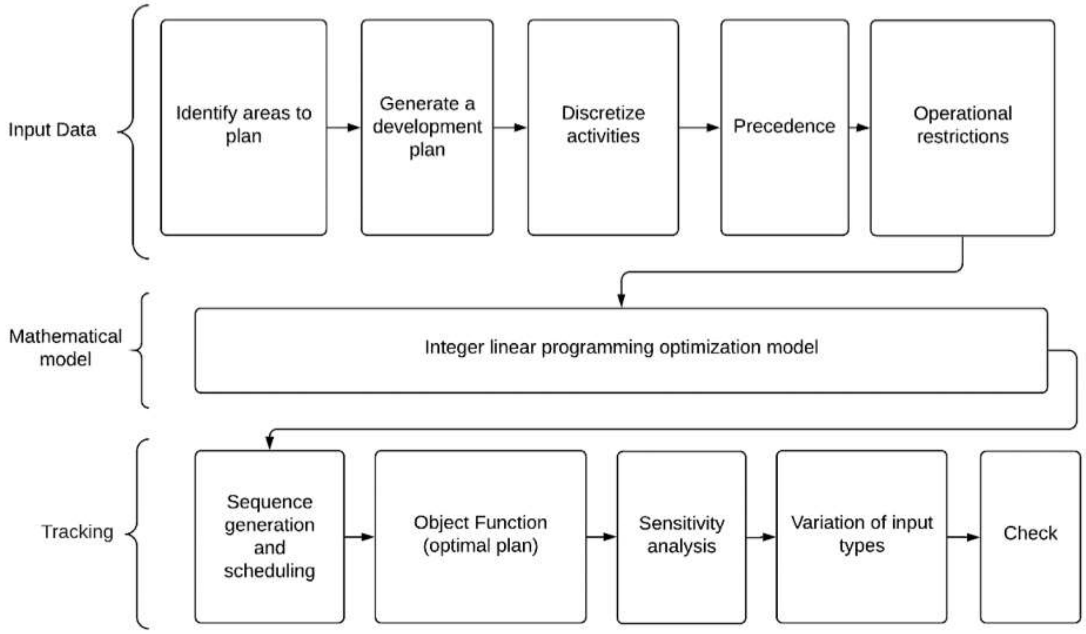


Figure 1 **Preparation of input data, utilization of mathematical model and reporting of solutions**

Figure 1 presents some of the concepts described above, illustrating how the data has to be prepared and how the data interact with the mathematical model.

2.1.2 Drilling and blasting operational cycle

For modelling using direct block scheduling, mine unit operations are subdivided into several activities, which are presented in Figure 2.

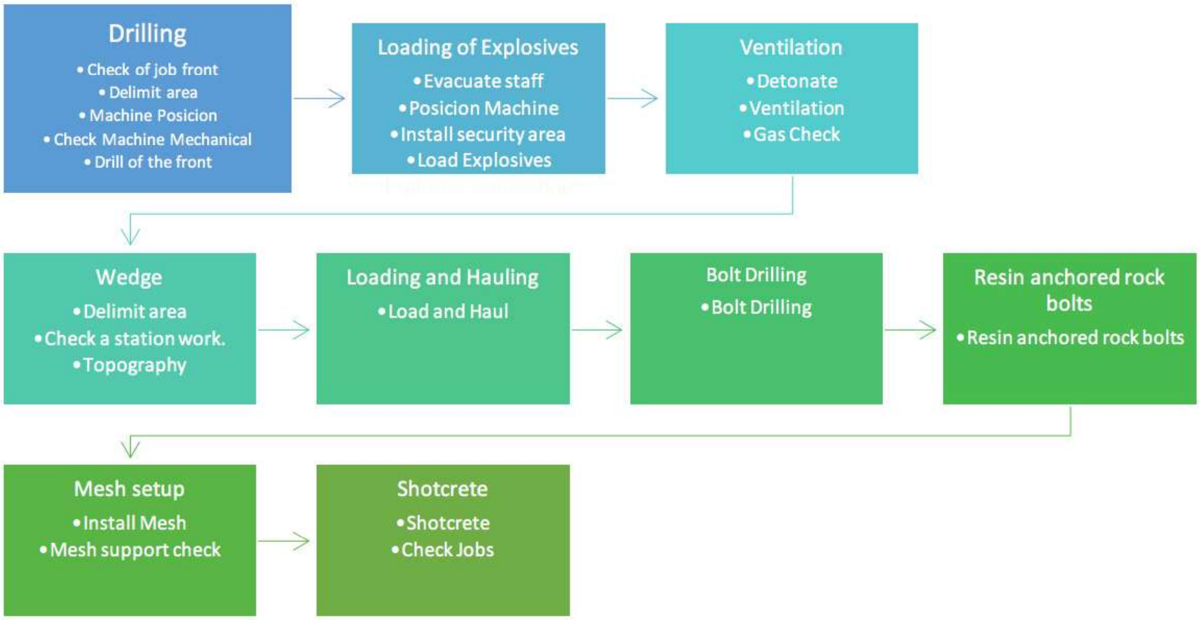


Figure 2 **Decomposition of horizontal construction unitary operations into activities**

A relevant case is that of the operation of "Loading of Explosives", which contains the following subactivities: zone isolation, machinery positioning, installation of safety perimeter, explosive loading, and connection of explosives. Because of safety regulations, this operation cannot be interrupted at any point, and therefore, we consider two potential ways of modelling this operation:

The operation is considered as a unique whole, consisting of all the subactivities.

The operation is split into two parts: (1) zone isolation, machinery positioning, installation of safety perimeter, and (2) explosive loading and connection of explosives.

2.1.3 *Effective Time*

The job time is divided into several parts from the beginning and including the effective working time until the end (Figure 3).

Figure 3 **Nominal shift time**

- Safety talks and Travel time: This consists of the time that workers participate in the safety talk and then move to the mine. In this period, only the ventilation activities of horizontal tasks can be carried out.
- Effective Working Time: This is the time workers are on the front performing preparation activities (except ventilation).
- Travel time and break Time: During this time, workers go to lunch/break and return. During this period, only ventilation activities of horizontal tasks can be carried out.
- End Turn: This is the time that workers end their shifts. In this period, only ventilation activities of horizontal tasks can be carried out.

2.2 Modelling construction activities using Direct Block Scheduling

We consider four different ways of modelling the activities using DBS: uninterrupted operation, fully flexible interruption, mixed operation, and improved mixed operation. The latter is the model proposed here.

Table 1 **Summary: Different strategies tested vs. model-strategy proposed**

Model	Description
Uninterrupted Operation	This is a pessimistic model, which assumes that operations have to be scheduled in such a way that there are no possible interruptions (i.e. no subactivities), which means that the result is an upper bound of the total construction time.
Fully-Flexible Interruption	This model assumes that activities can be interrupted as much as required in any subactivity. This is not completely realistic, but provides an optimistic result, which can be used as a lower bound of the total construction time.
Mixed Operation	This model takes into account that the explosive loading task cannot be interrupted but allows other activities to be interrupted. As such, it is a more realistic way to schedule the activities.
Improved Mixed Operation(model proposed)	This corresponds to the case where all operations, except the explosive loading can be interrupted, and the explosive loading can be split into two (See Section 2.1.2)

3 Case study

The methodology was applied using the mining development plan of a mining operation, which is carried out through the Panel Caving method and is located in Chile. The five typical levels of an operation of its size are considered, which include (1) undercut, (2) production (3) ventilation, (4) loading level, (5) ore crossing systems.

To implement the base plan in the mathematical model, about 110,000 activities were defined, and 4 cases were analyzed according to the models described in Table 1.

Table 2 Summary of cases in terms of activities and constraints

		Activities	Precedences	Constraints
Reference Plan		600	700	200
Short-Term Model	Uninterrupted Operation	111,000	250,000	253,750
	Fully-Flexible Interruption	111,000	250,000	240,000
	Mixed Operation	111,000	250,000	241,925
	Improved Mixed Operation	111,000	250,000	241,375

3.1 The base plan

A long-term plan was separated into two-month horizons for the purposes of this case study. This plan provided guidelines for all activities necessary to discretize more effectively over a realistic time period. It also indicated when some of the main milestones had to be developed. The details of the activities to be carried out on a monthly basis are shown below.

Table 3 Activities to be carried out on a monthly basis

Number of days	60 days
Horizontal Development	306 meters
Vertical Development	294 meters
Hydraulic Fragmentation	8 units
Walls	12 units

3.2 Model parameters

Table 4 Activity horizontal development

Activity	Time(hours)
Drill	3 hours
Load Explosives	3 hours
Ventilation	2 hours
Wedge	2 hours
Load and Haul	2 hours
Bolt Drilling	3 hours
Resin anchored rock bolts	3 hours
Mesh	3 hours
Shotcrete	3 hours
TOTAL	24 Hours

Table 5 **Vertical development**

Activity	Raiser Borer		Blind Hole	
Fixed activities				
Concrete base construction	17 hours		1 week	
Forged concrete base	1 week			
Assembly team	3 days			
Disassembly team	1 week		1 week	
RB Concrete base retreat	1 week		1 week	
Variable activities				
Pilot shot drilling	13 inches	11 m/day		
Ream	Ream 2 meters		Ream 1.5 meters	5 m/day
			3 m/day	

4 Model comparisons

Each model above was compared with the proposed Improved Mixed Operation. Each model has its limitations, which were explained and defined in section 2.2.

4.1 Uninterrupted operation

The work scheduling time for the construction of the horizontal developments of the undercutting level was more (1600 vs 1441) than the model proposed (Improved mixed operation), but the final computation time is less; this occurred because of less restriction and precedence.

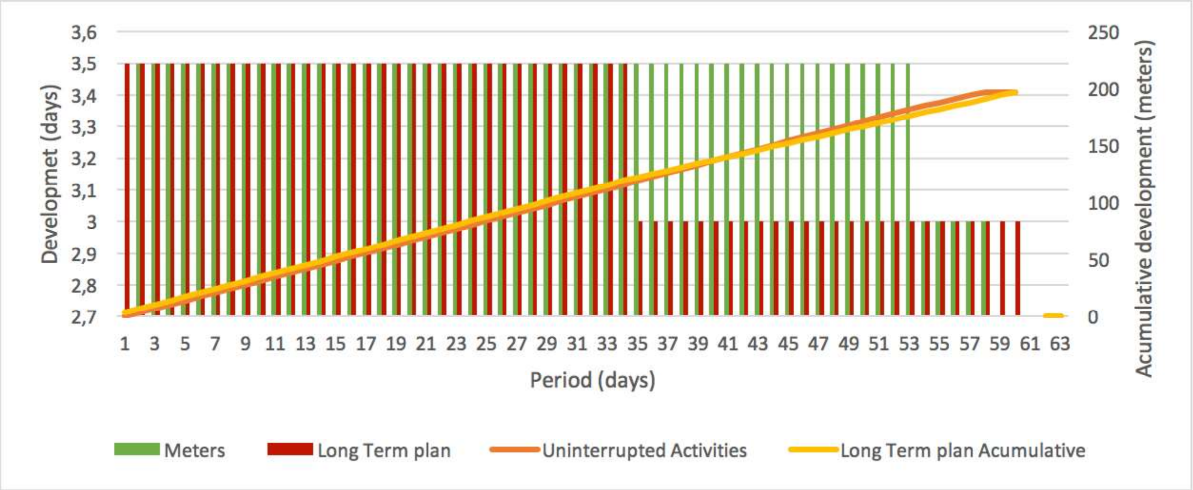


Figure 4 **Uninterrupted operation undercut development**

4.2 Flexible operation

It is observed that the construction time of horizontal developments is less than any other alternative. The generation of plans without any operational restriction (any activity can be interrupted) allows for plans with a very short time; this is unrealistic since there are activities which must be completed and thus require some restriction.

The time variation is around 5% compared to the proposed model. This is mainly due to the interruption of activities such as face drilling and loading of explosives.

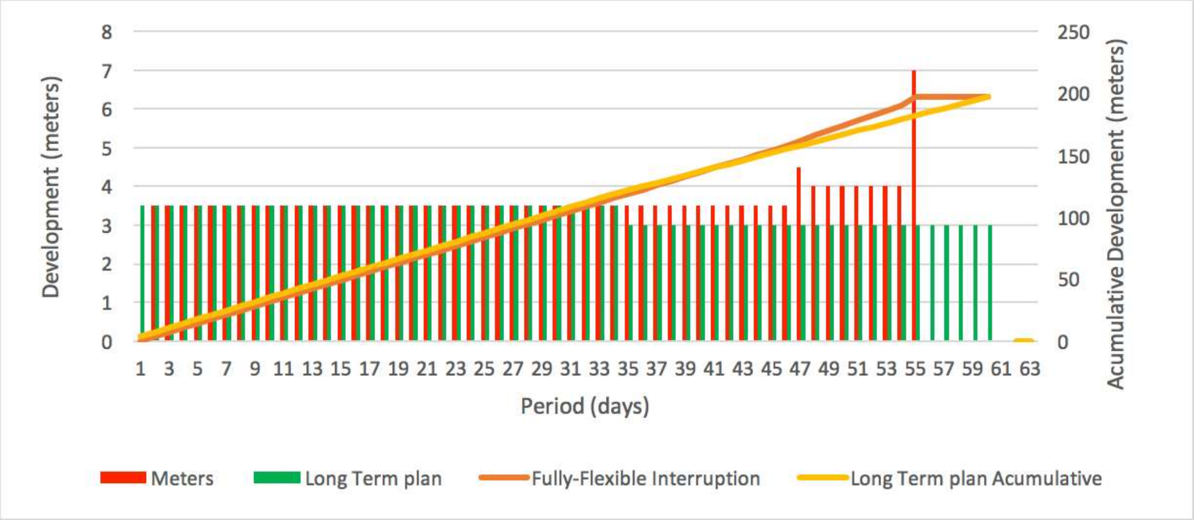


Figure 5 **Flexible operation undercut development**

4.3 Mixed operation

The generation of plans with certain restrictions generates plans that are closer to reality with a variation of + 3% compared to the proposed model.

The more Restrictions we enter into the system, the more computation time is required, and the time scheduling tends to increase.

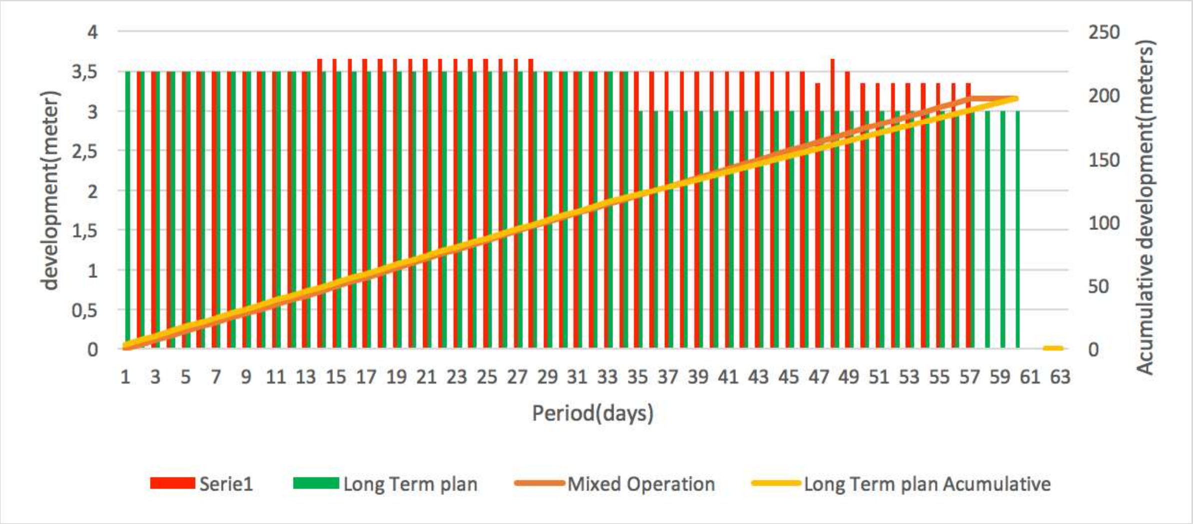


Figure 6 **Mixed operation undercut development**

4.4 Improved mixed model

The proposed model generates a plan which is realistic with almost zero time variation, and allows us to maintain critical activities without interruption.

It is observed in the graph that the behavior is very similar to the base plan; it only varies in its final part.

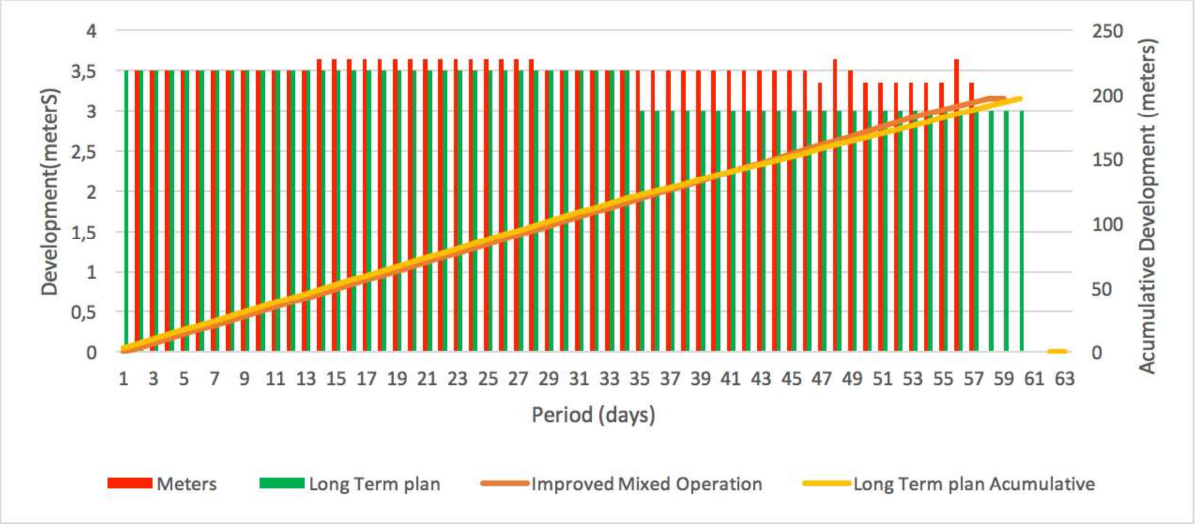


Figure 7 **Improved mixed operation undercut development**

5 Analysis and discussion

Comparison table different models

Table 6 **Time**

Model	Construction time (hours)
Mixed operation	1,500
Uninterrupted activities	1,600
Improved mixed operation	1,441
Fully-Flexible interruption	1,400

Table 7 **Model comparison**

Model	Construction time (hours)	Delta (%)
Base Case	1440	
Uninterrupted activities	1,600	+10%
Fully-Flexible interruption	1,400	-4%
Mixed operation	1,500	+3%
Improved mixed operation(proposed model)	1,441	0%

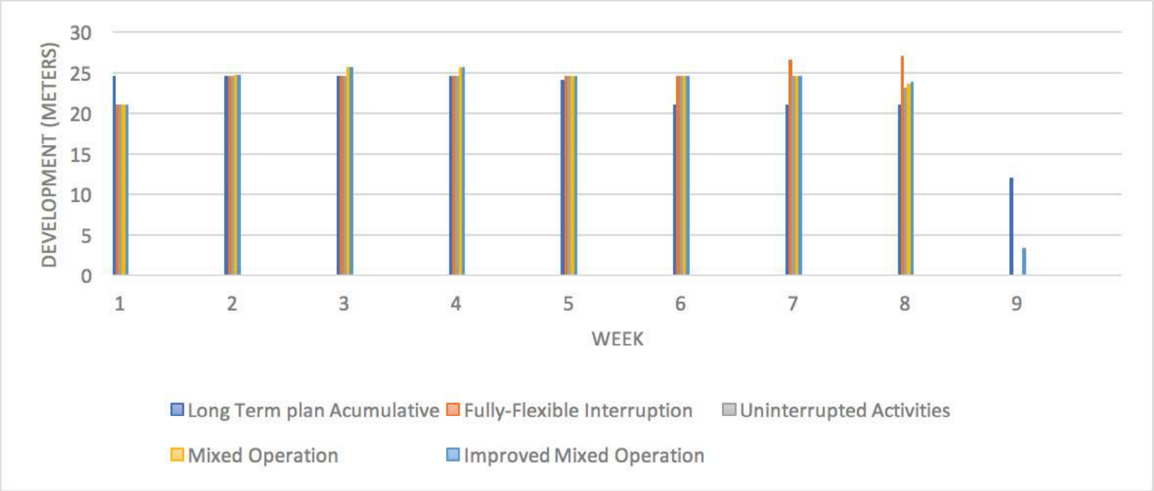
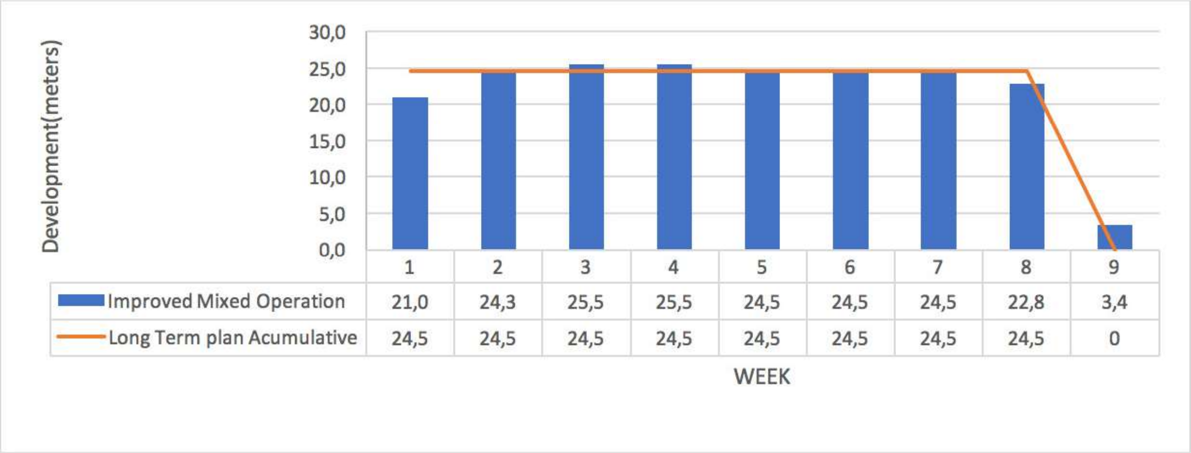


Figure 8 Development (meters)

5.1 Metrics compared

One result of the model was that the activities of the long-term plan were disaggregated such that all the activities were completed in eight weeks, leaving the ninth week without activities. This reveals that these activities were reorganized effectively, fulfilling the time and target requested by the client.

With respect to the analysis of the base plan vs improved mixed operation, the Figure 10 shows that the progress discretised constantly in the proposed model, since this is where the activities are reassigned and generates an optimization of resources and time.



	1	2	3	4	5	6	7	8	9
Improved Mixed Operation	21,0	24,3	25,5	25,5	24,5	24,5	24,5	22,8	3,4
Long Term plan Acumulative	24,5	24,5	24,5	24,5	24,5	24,5	24,5	24,5	0

Figure 9 Progress discretised constantly in the proposed model

Table 8 **Final results**

Milestone	Deadline (Long-Term Plan)	Fulfillment
Horizontal developments	✓	✓
Vertical developments	✓	✓
Walls	✓	✓
Railways	✓	✓
Intersection fortification	✓	✓
Extraction points	✓	✓
Ventilation Developments	✓	✓

The model scheduled all activities associated with the program for the 2-month period, which corresponds to the program's time horizon.

The horizontal development plan is developed with the same operational sequence that gives us a long-term plan but in a discretized way. It also delivers the activities that must be carried out on each work front for the different levels (Undercut, production, transport and ventilation levels). However, by incorporating historical data on the performance of the development plan, the availability of resources by level, and the prioritization of higher impact jobs, such as mineral passing systems, the DBS technique provided a more efficient and effective plan.

6 Conclusions

In this paper we address the problem of short-term scheduling of construction activities in an underground mine operating using the panel caving method. To address the problem, we adopt the Direct Block Scheduling (DBS) technique, which is a methodology used for open pit mine production scheduling, but which allows efficient computation for large-scale activities subject to precedence constraints and resource availability.

The proposed methodology allows the automation of the mine development planning process, generating equivalent solutions that are operationally correct and that meet the defined times. The mathematical optimization model generates redistributed plans compared to the original plan, respecting operational precedents, and distributing the largest number of activities per period.

We apply the methodology in a real case study (base plan), considering different ways of utilizing DBS for modeling the problem and generate several plans accordingly, considering two theoretical cases (optimistic and pessimistic) as well as two practical ones.

The two practical plans scheduled all activities within the maximum period set for 2 months, however, while these two schedules meet the long-term construction targets, they show a slower progress with deviations between 0% and 10% (depending on the case). However, given the level of detail of the activities, these plans are potentially more reliable in their duration than the long-term one.

Another advantage of the proposed methodology is the speed of generating plans, which allows time to be gained for analyzing possible scenarios or doing sensitivity analyses, recalculating plans during execution, obtaining higher resolution solutions on a scale of weeks or days, and considering variability in the execution times of the activities. These last two options are being explored for use in the case study operation. Finally, the methodology shows relevant flexibility in terms of modelling, meaning that different operational modes could be abstracted and optimized using the same framework.

The results suggest the approach proposed here can improve mine development programming in terms of time and efficiency. In addition, the model provides the ability and flexibility to test various development scenarios, a capability that does not currently exist due to the way experts create programs.

Acknowledgements

The authors would like to thank the Advanced Mining Technology Center and CONICYT/PIA Project AFB180004 for supporting this work.

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