Underground development sequencer and scheduler considering constructability

Winston Rocher , Enrique Rubio and Nelson Morales
Delphos Mine Planning Laboratory, Advanced Mining Technology Center, Universidad de Chile

ABSTRACT

A common practice in the mining industry is to decompose the planning process into different tasks so that the overall process and specific schedules can be constructed easily. Nevertheless, currently there are some adverse effects, such as not capturing the real value of a project by not taking into account the construction of several underground drifts and general infrastructure. Then the common practice is to compute mining sequence and cut-off grade profiles over the life of the mine without constitutively integrating the development schedule as a means to measure the constructability of a given mine design and sequence. Thus, the investigation summarised in this paper shows a novel, integrative way of treating an underground mine sequence and production schedule while considering drift development scheduling. Moreover, it is thought that, because of this original model, the whole underground production scheduling exercise must concentrate on combining the development and the production scheduling to compute a robust and a feasible production schedule.

In order to quantify the effect of the conventional way of viewing the planning, the concept of the Building Information Model (BIM) needs to be used, which was postulated by Charles Eastman and has been used extensively since the late 1970s. BIM takes other aspects of a project into account, considering at the same time the spatial relationships, light analysis, quantities and properties of building components.

This paper presents the basis for an optimisation model that allows for defining the sequence of the mining development so that the production plan can be achieved. For this, the model considers space dimensions, time, pattern or strategy, cost, benefit and resources available. Tests were performed considering a block caving method and finally showed the main conclusion, that production sequence changes when the building capacity is considered.

INTRODUCTION

A common practice in the mining industry is to decompose the planning process into different tasks so the overall process and specific schedules can be constructed easily. Nevertheless, currently there are some adverse effects without capturing the real value of a project by not taking into account the construction of several underground drifts and general infrastructure. Examples can be found of mines that cannot fulfil their production's budgets due to the inability to fulfil infrastructure development requirements. In fact, El Teniente Mine published in the MassMin 2008 Congress that in 2002 they had a 61% fulfilment of preparation and a 70% fulfilment of production, highlighting the importance of the topic [1].

In analysing this focus, three important subjects are found: construction techniques, rock mass support and construction sequence. The first two parts are specific civil development areas and the last one involves the concept of how a mine project is evaluated and what the value promise is. The common practice is to compute mining sequence and cut off grade profiles over the life of the mine without constitutively integrating the development schedule as a means to measure the constructability of a given mine design and sequence, so the feasibility of construction is short term planning work. This is called *work breakdown structure* [2], and it is a possible and reasonable view when we have huge problems like mining optimisation; nevertheless it is important to ask what consequences this has. Does the project have the same value? Does the production sequence if the different and reliable problems of a mine are considered? Who makes the development schedule? What knowledge of a production plan is there?

The research summarised in this paper shows a novel, integrative way of treating an underground mine sequence and production schedule while considering drift development scheduling and two types of implementations of it. Moreover, it is thought that, because of this original model, the whole underground production scheduling exercise must concentrate significantly more on the development scheduling rather than on the production scheduling, since the production is a main outcome of a given development schedule. This logic has culminated in a new mine tool called Underground Development Sequencer and Scheduler, or UDESS, which can sequence a project more closely to reality and control the eventual loss of flexibility. This tool proposes to integrate what has traditionally been seen as a decoupled process of civil engineering and manufacturing engineering into a whole, since there are tremendous logistical interfaces between production dynamics and construction processes that interact and interfere with each other when operating an underground mine. Furthermore, in order to quantify the effect of the conventional way of viewing the planning and to make the information easier to manage, the *building information model* concept needs to be used. BIM takes the aspects of a project (spatial relationships, quantities, profits and properties of building components) and makes the necessary links between the visualization, which is especially of interest. In applying this notion, the results can be seen as if on a movie screen with the advantage of being able to zoom, rotate and identify every segment.

DEVELOPMENT PROGRAMME REMARKS

There is truth to the idea that a holistic view will be always better in the final result, but this is practically impossible when considering the efficiency needed to calculate and understand the problem, such as in the typical problem of a development plan. This statement is true mainly because, when combining the construction of a given civil endeavour and the production manufacturing, several logistical issues such as inventory and infrastructure need to be carefully looked at in order to avoid losses that can deteriorate the value of a project.

An activity programme follows the strategic plan, takes advantage of the maximum resources, restricts the time and avoids problems, but unfortunately we can see a few intermediate points of the path that were programmed. This causes deviations from the plan, either a kind of entropy or simply because there are not enough conditions (resources, capacity, interference times or esteemed advance rates) to go to the next expected point. Next, deflectors have to be applied to correct the path, but not without an additional cost.

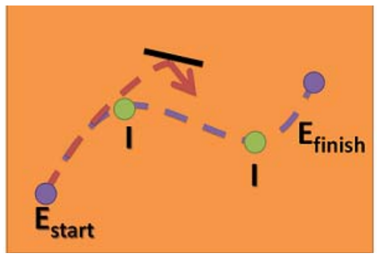

Figure 1 Deflector's action

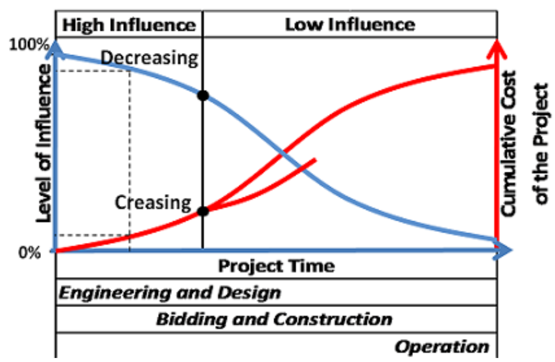

Figure 2 Influence in the project time [2]

This cost could be reflected in many ways, sometimes only delaying the entire project and other times sacrificing a percentage of the project value. For this reason, the new question must be: what percentage? The answer depends, but the actions that are taken at the beginning are the roots of the future, making them the most important, or at least making them the factors which have higher influence and low cumulative cost. Therefore, it makes sense to stop for a while and think more about the congruence of the design and planning while room for flexibility still exists.

The main challenge to address in the research summarised in this paper is to formulate a robust, mathematical programming model that can sequence and schedule the construction of horizontal and vertical excavation over the life of the mine, which are called segments or activities in this study. It must also facilitate the flow of ore across the mining system at the same time as scheduling the opening of new production areas, thereby maximising the *net profit*.

Before starting the mathematical problem of sequence and schedule development, it is important to summarise the operational constraints applicable to a mining project.

Maximum development rate: This states the maximum feasible quantity of metres to be done at any given time. This constraint is usually linked to the construction technique and the geotechnics of the ore body, so segments allocated in different mineralisation zones can have different rates only in hardness.

Minimum development rate: This defines the minimum feasible quantity of metres to be done at any given time when the activity has already started. This takes place in activities which have to be developed without stopping, or with relatively few stops, like water pumping or any activity that is connected to the draw ratio and defines a temporary relationship between one draw point and its neighbours.

Cost or profit: These, including the production activities, have the labour of motivating the sequencing and scheduling depending on the objective function, which in this case is the NPV. Moreover, this could differentiate alternatives of design and, in some cases, be decided not to develop if there is not enough profitability.

Required resources: These are essential for the correct or real analysis because they indicate which materials, machines, workers or time are necessary for the labour. Then it can be said if one segment needs a jumbo machine, another a TBM and another a raise borer machine.

Available resources: These state the total available resources in the mine at any period. This means that the mine staff can be limited because it is infeasible to have too many people inside the mine due to security. It also means that the total available machines or whatever supplies, like shotcrete, steel sets or specific type of bolts, can be limited as well. Ultimately, this defines the interference time between different activities, preventing achievement of the maximum development rate. A large number of resources will give faster progress rates, but increase the capital cost used and the inefficiency of stocks required.

Physical precedence [4]: This defines the continuity of tunnels and shows that for constructing one segment, all the segments of tunnel that are behind of it must be developed. In other words, it makes it possible for machines to get to some point. Obviously this cannot be a variable and is supported in a given mine layout.

Operational precedence [4]: This defines specifically which activities or segments must be done before another, but not in a physical way. It is different from the physical precedence because it is related to the mining system and makes the flow of ore to the surface possible. Inside this category are included crushers, conveyors, load out bins, etc. Consequently, like a reflection of the mining system, it depends on the operational precedence which kind of mine should be created or what kind of results should be obtained.

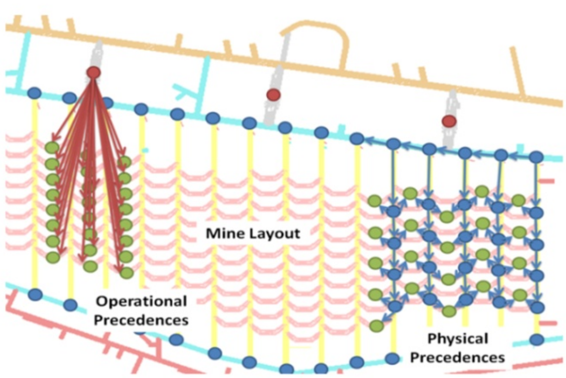

Figure 3 Precedence

Production constraints [5]: These state the parameters that have to obey certain mining methods. In block caving there is a draw rate, which controls the flow of muck, and the draw ratio already mentioned. This will control the dilution entry point and the damage of the production level. Most importantly, it gives a space consistency in relation to the production activities.

Period constraints: These give accuracy and play an essential role in how big the optimisation problem is. As a result, reasonable period lengths must be taken in relation to the duration of the activities and the time term view.

OPTIMISATION MODEL

According to the problem of optimising *net present value*, a set of time periods $t = 1, 2, \dots, T$ is considered, where $T \in N$ is the *time horizon* and the amount of time that the project will be evaluated.

Activities and economic parameters

A set A of activities must be considered in order to fulfil the entire mine design. Then, for an activity $i \in A$, a cost or profit v_i^+ is considered for starting the activity i, v_i^- for finishing the activity and v_i for developing the activity. This way, fixed costs are incorporated that don't depend on the duration or length of the activity and basic economic parameters for the objective function.

Decision variables

The model considers three sets of decision variables with which the optimisation is performed: those associated with the beginning of an activity to define when it has started, those associated with the ending of an activity to know when it has finished and not just stopped, and those associated with the carrying out of activities that reflect the intensity with which it is developed. Thus, the decision variables are:

P_{it} = percentage of activity i developed at time-period t

The following are associated with the beginning and, similarly, with the ending of an activity:

$$s_{it} = \begin{cases} 1 & \text{activity } i \text{ has started by time-period } t, \\ 0 & \text{if not.} \end{cases}$$

$$e_{it} = \begin{cases} 1 & \text{activity } i \text{ has not yet ended by time-period } t, \\ 0 & if\ not. \end{cases}$$

Now, the status of an activity in time can be determined, like in the following example:

Figure 4 Beginning and ending variables for a specific activity in time

To simplify this notation, another notation that takes advantage of the definition of s_{it} and e_{it} is introduced for the beginning and ending variables as follows:

$$\Delta x_{it} = \begin{cases} x_{i1} & t = 1, \\ x_{it} - x_{it-1} & t > 1. \end{cases}$$

In this new notation there is only one period that is different from zero, which allows identifying when every activity starts or ends more effectively.

Objective function

Now that the basic ideas have been defined, the objective function that maximises the overall *net profit*, discounted by a factor $\alpha < 1$ that shows the time effect depending on the assumed risk, can be formulated as follows:

$$V = \sum_{t=1}^{T} \alpha^{t-1} \sum_{i \in A} (v_i p_{it} - v_i^+ \Delta s_{it} - v_i^- \Delta e_{it}) \tag{1}$$

Constraints

Variable definition and relations

There are some basic definitions regarding the decision variables that make sure that they are represented clearly. In this case, Equation (2) shows that there is only one start time and one end time. Equation (3) means that to develop one segment, it has to be started and not yet finished, meanwhile, at the same time, the progress at any given period cannot be greater than 100% of the total progress.

$$\Delta s_{it} \geq 0, \qquad \Delta e_{it} \leq 0 \qquad (\forall i \in A)(\forall t = 1,2, \ldots, T) \tag{2}$$

$$p_{it} \leq s_{it}, \qquad p_{it} \leq e_{it} \qquad (\forall i \in A)(\forall t = 1,2, \ldots, T) \tag{3}$$

$$1 - e_{it} \leq \sum_{s \leq t} p_{is} \qquad (\forall i \in A)(\forall t = 1,2, \ldots, T) \tag{4}$$

$$p_{it} \leq v_{max\,i} \qquad (\forall i \in A)(\forall t = 1,2, \dots, T) \tag{5}$$

Additionally, Equation (4) says that to end an activity it is necessary to do 100% of the labour, and finally Equation (5) sets the maximum development rate for all segments as was already defined.

Precedence

Precedence constraints, physical and operational, are modelled as follows at the same time because they are not any different for the model. Then a set of requirements $P(i) \subset 2^{A-\{i\}}$ are considered for each activity i, where one requirement can be a group of precedence activities. The idea is that activity i is ready to be started if there is a requirement $P \in P(i)$ that has been fulfilled, that is, each activity of $j \in P$ has finished. Consequently, it may be possible for a specific activity to belong to more than one $P \in P(i)$ and therefore give different alternatives of precedence. This means that at the same time there are relationships of the *and/or* type. This is illustrated in the next diagram, which also shows that there are different precedence groups to start an activity:

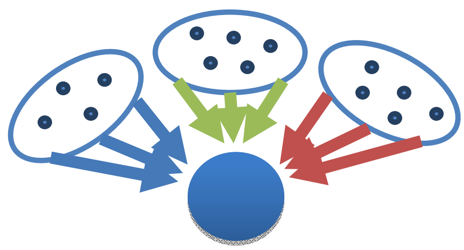

Figure 5 Groups of precedence

Then, by introducing the following auxiliary variable that will help to write the precedence constraints, whether or not a given requirement has been fulfilled can be evaluated.

$$r_{iPt} = \begin{cases} 1 & \text{activities in group } P \in P(i) \text{ have been finished by time-period } t, \\ 0 & \text{if not.} \end{cases}$$

Therefore, Equation (6) shows that when at least one physical and operational requirement of groups of precedence is accomplished, it is available to start an indicated activity, whereas Equation (7) says that only if all the activities or segments related have finished can it mark that requirement as '1'.

$$s_{it} \leq \sum_{P \in P(i)} r_{P\,t} \qquad (\forall i \in A)(\forall t = 1,2, \dots, T) \tag{6}$$

$$r_{Pt} \leq 1 - e_{jt} \qquad (\forall i \in A)\big(\forall P \in P(i)\big)(\forall j \in P) \tag{7}$$

It is worth noting that as a consequence of constraint (6), it is necessary to wait for a different period to start the next activity if its precedence constraint is correct. This could be solved using the following variant, which frees the variable s_{it} one period. It has to be used carefully because it can become absurd when many consecutive activities are performed during the same period.

$$s_{it} \leq \sum_{P \in P(i)} r_{P\ t+1} \qquad (\forall i \in A)(\forall t = 1,2, \dots, T) \tag{8}$$

Resource consumption

Finally, we take a set R of available resources and a required resource c_r^i of resource $r \in R$ for developing activity i. The overall availability of resource r at time period t is denoted as R_t^r.

$$\sum_{i \in A} c_r^i p_{it} \leq R_t^r \qquad (\forall i \in A)(\forall r \in R)(\forall t = 1,2, \dots, T) \tag{9}$$

This means that all progress in the mine is bounded by the capacity of labour, ore flow or even the total cost that the investors are willing to pay per period. So, as it has already been stated, this brings enough conditions to develop a particular activity.

UDESS

There were two different implementations developed in this research, the first one was focused on understanding the problems and their complications, and the second one was thinking of the direct applications in the industry for better managing the information and applicability. UDESS was programmed on python and optimised on the gurobi solver version 3.0.2, except for some previous steps when the data was being prepare and different supports for certain purposes were used, such as java and other mining packages.

Xml Implementation

For this view, there is a step prior to the optimisation and it is used to create a precedence digraph, which involves all types of precedence and assigns the attributes of the different activities in terms of profit or cost, productivity, length, etc., illustrated like a cycle in Figure 6, in another step.

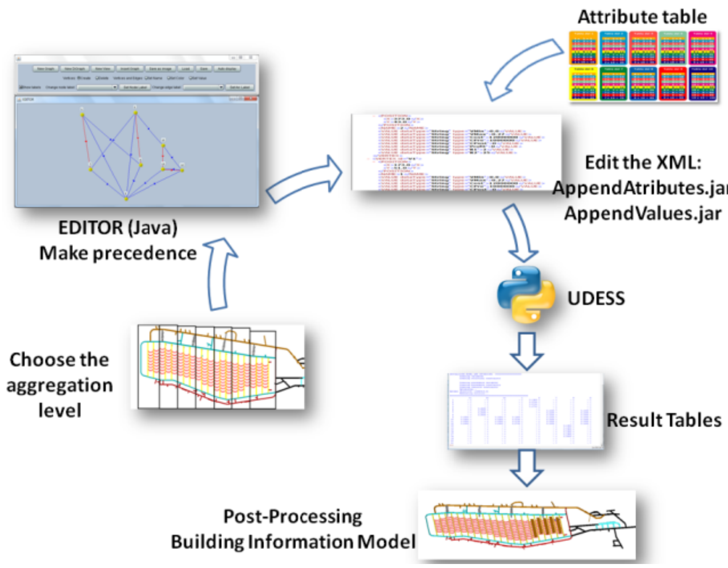

Figure 6 XML Implementation

The start of the cycle considers implicitly the desired aggregation level as the first action, which determines the time term that is applicable to the required optimisation: a long-term optimisation with big activities or a short-term optimisation only in one mine sector. Then, supported on a java applet called *editor*, a digraph can be made connecting the precedence of the different activities and an XML file with those relations can be exported, but without other detail. Next, the user has to take into account its labour because it needs to create every activity manually, making the procedure too tedious. Moreover, because it is a digraph, when giving different requirements it begins to be too many lines to understand graphically what the mine scheme is.

Then, with the help of other programming codes, it is possible to introduce attributes to the XML file such as economic parameters and required resources. Consequently, the file is prepared to be optimised in UDESS. Finally, the results of the optimisation are put in a set of tables, including the activities' progress by period, which is then loaded into *autodesk naviswork* with a CAD for animating the sequence and seeing the consistency for a mine operation.

After testing this approach it was observed that it was not flexible enough to apply for several mine-wide applications, especially when incorporating production constraints. Thus, it was decided to move to a commercial package called Mine2-4D to prepare all data needed for the optimisation.

Mine2-4D implementation

There was an alternative view to enhance with Mine2-4D. There, the design can be drawn, precedence can be incorporated and maximum rates can be inserted along with whatever attributes the user wants. The advantage of this is that the activities can be loaded from CAD knowledge, like segments, and the user doesn't have to explicitly make all the precedence relations or create activities one by one. The result is again a table with all the information and a large list of activities that may be managed with other software from the Mine2-4D package, *Enhanced Production Scheduler*.

Therefore, one important stage before optimisinge the sequence or schedule, for resolving the problem in a lighter way, is reblocking the activities list. To do this, we consider that two consecutive segments will be combined when one of them is the unique predecessor of the other and at the same time the second one is the unique successor for the first one; we can keep all the information but in fewer quantities of activities, which is overly desired for the optimisation.

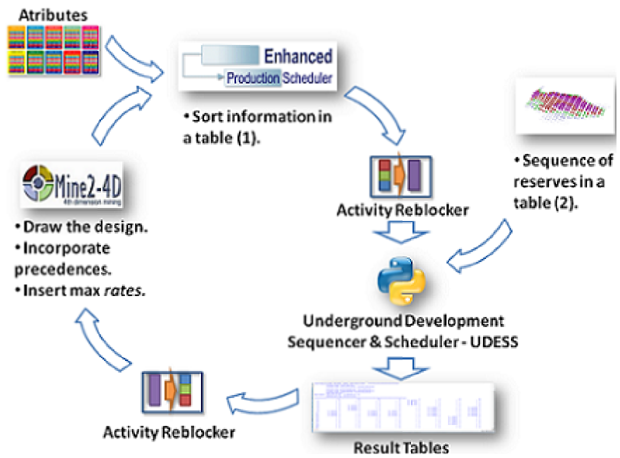

Figure 7 Mine2-4D implementation

Another change is that the production plan comes from another analysis, which takes care of the production constraints and is loaded in UDESS with a different file. Then, the machine is responsible for connecting the production activities with the development, like in this case searching which drawbell is the nearest from a determinate extract column. It is worth noting that, in fact, this creates the possibility that some basic unit of production isn't be extracted, or at least that delays their extraction, changing the optimal production solution and creating the need to revaluate it.

RESULTS AND DISCUSSION

A minimal underground mining design considered to test the model and implementation with Mine2-4D, which has hopeful results. For these first tests, for lightening the optimization, it was considered that there is a unique sequence. This means that the construction of tunnels has a previously determined direction.

With an efficiency of the activity reblocker of 40%, scenarios of 1022 activities were run with a time horizon of 55 periods that had the length of a month and involved production and caving levels from an actual operation of a block caving mine. This mine produces 25 [ktpd] and works with LHD of 7 [yd^3] and conventional construction techniques, which is to say, drill and blast. The mining system consists of the loader to the ore-passes for a transport level where the ore goes to surface.

This optimisation took 7.5 hours to finish in an Intel Core Duo 2.4GHz with 3Gb RAM with the following two effects: One was related to the schedule, seeing that many activities change their order to start when they don't have enough resources and, as a consequence, it was noted that one sector must be development before another for better economic results. The second effect was the loss of value while we putting it in a tighter constraint, reaching to the point that there wasn't any economically viable project. With these two effects, it was demonstrated in a simple way that there is a close relation between the constructability and the production, which would change the form of viewing a mine for operational purposes because would need now a different supply programme or have to change the position of the machines between mine sectors.

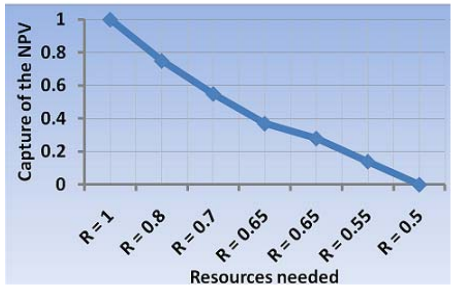

Figure 8 Capture of the NPV with resources constraint

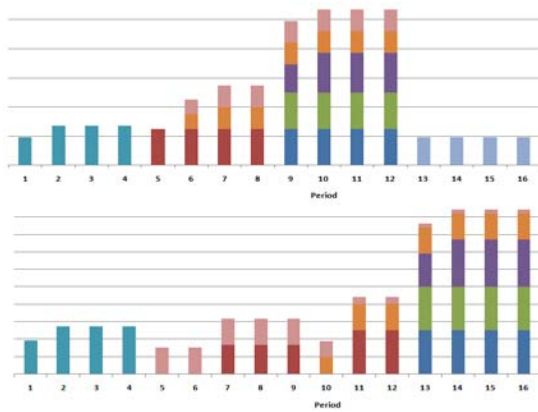

Figure 9 Different schedules of mine sectors with varied optimised conditions

The results show that the implementations work as expected, giving coherent outcomes with accepted shapes of *S curve* [2] of cost and progress metres, and indicating that it is possible to perform new tests. However, in this case two new problems to solve appear:

- It works at the limit of computer capacity: this implies that more caution is required when choosing the aggregation level and time horizon.
- For a reliable result it needs to have periods of time comparable to the time that it takes to fulfil activities. If a longer time length is considered, the model will include idle times. To solve this problem, a variant in the model is incorporated, giving flexibility. Despite the fact that one could take a longer period of time, if no caution is taken it would bring the opposite problem, the model would start to overlap consecutives activities.

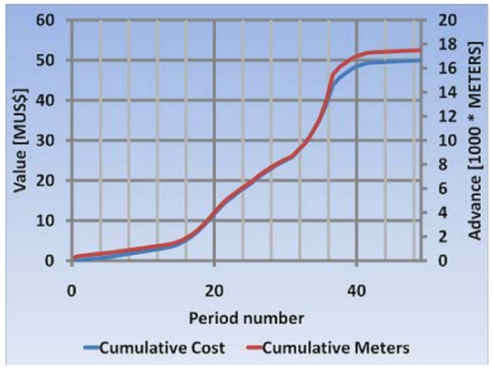

Figure 10 Cumulative cost and metres in the life of the project

SUMMARY AND FUTURE WORK

It is essential to conciliate production and development plans and must be a constant preoccupation for mine planners. From this point of view, the Underground Development Sequencer and Scheduler research creates an important advantage in the current mine market because there are no optimisation tools like this for underground, long-term mine project and it is clear that the computational capacity provide strong help. As a result, a mine project is being supported on a reasonable analysis, searching for the best economic alternative and giving a schedule according to its specific resources and requirements.

Finally, there are some restrictions to the implementation that have to be tested and determined with more accuracy what scope this tool would have, although it would define the success of the resultant production schedule. Furthermore indicators of reliability have to be incorporated, but despite this, it has already demonstrated the UDESS's ability to deliver consistent results and help where before there was only the experience of the engineer.

REFERENCES

Díaz, G., Morales, E. (2008) *Tunneling and construction for 140,000 tonnes per day* – El Teniente mine – Codelco Chile. In: Massmin 2008 Congress, Luleå, Sweden. [1]

Serpell, A., Alarcón, L. (2003) *Planificación y control de proyectos*. Ediciones Universidad Católica de Chile. [2]

Newman, A., Kuchta, M. (2007) *Using aggregation to optimize long-term production planning at an underground mine*. Retrieved from http://inside.mines.edu/~anewman/. [3]

Rahal, D., Smith, M. (2003) *The use of mixed integer linear programming for long term scheduling in block cave caving mines*. Retrieved from http://www.onemine.org. [4]

Rubio, E., Diering, T. (2004) *Block Cave production planning using operation research tools*. In: Massmin 2004 Congress, Santiago, Chile. [5]

Sons Inc., New Jersey, USA, pp. 517-544.