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Eight-Dimensional Planning – Construction of an Integrated Model for Mine Planning Involving Constructability

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ABSTRACT

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, 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, quantities and properties of building components, but especially some kind of model visualisation, which is the advantage to be incorporated.

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 the space dimensions, time, pattern or strategy, cost or benefit, precedence and resources available. Tests were performed considering a block caving and sublevel open stoping method. Finally these tests 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 budgets due to the inability to fulfil infrastructure development requirements. In fact, Díaz and Morales (2008) reported that in 2002 they had a 61 per cent fulfilment of preparation and a 70 per cent fulfilment of production, highlighting the importance of the topic.

In analysing this, three important subjects are found:

1. construction techniques,
2. rock mass support, and
3. construction sequence.

The first two parts are specific civil development areas and the third involves the concept of how a mine project is evaluated and what the value promise is. The common practice is to compute mining

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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 (Serpell and Alarcón, 2003), and it is a possible and reasonable view when there are huge problems like mining optimisation. Nevertheless, it is important to ask what consequences this has. Does the project have the same value? Is the production sequence different 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 is still underway and was conducted through this year. This research shows a novel, integrative way of treating an underground mine sequence and production schedule while considering drift development scheduling and two types of implementations. Moreover, it is thought that, because of this original model, the whole underground production scheduling exercise must concentrate significantly more on development scheduling rather than on production scheduling, as 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 (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. The building information model (BIM) takes the aspects of a project (spatial relationships, quantities, profits and properties of building components) called dimensions, and makes the necessary links between the visualisation, which is of special interest. In addition, the traditional use of BIM in the last 20 years was in four-dimensions (4D) considering the three space dimensions plus time, in order to see the congruence between different parts of civil schemes. However, in mining bad decisions have big consequences, making it necessary to include up to eight-dimensions (8D), considering pattern or strategy, cost or benefit, precedence and resources available. 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.

For the purpose above, the following steps are carried out:

1. to learn about the current construction features, the interactions between the different activities to develop and the value thereof;
2. conceptualise mine infrastructure (production infrastructure, transport, ventilation, etc);
3. propose and develop the model;
4. perform basic implementation, defining the architecture, modifying parameters and consider extra variables according to the execution;
5. develop a method for constructing precedence considering a CAD file reading;
6. test implementation under different levels of aggregation such as: all or part of a mine, large and small mining operations, etc;
7. incorporate features of rationalist segments: value, geomechanics, tonnage, resources, etc;
8. enable the processing of large volumes of information with an intelligent heuristic processing; and
9. final tests in a case study (not incorporated in this paper).

DEVELOPMENT PROGRAM REMARKS

There is truth in the idea that a holistic view will always be better for 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. Only a few attempts on this have been made, emphasising mainly those carried out by Donal O'Sullivan and Alexandra Newman (O'Sullivan and Newman, 2010), nevertheless, it took too much time to prepare the information and the model applied used discrete variables.

An activity program follows the strategic plan, takes advantage of the maximum resources, restricts the time and avoids problems, but unfortunately can be controlled just a few intermediate points of the path that was 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. Deflectors have to be applied to correct the path (Figure 1), but not without an additional cost.

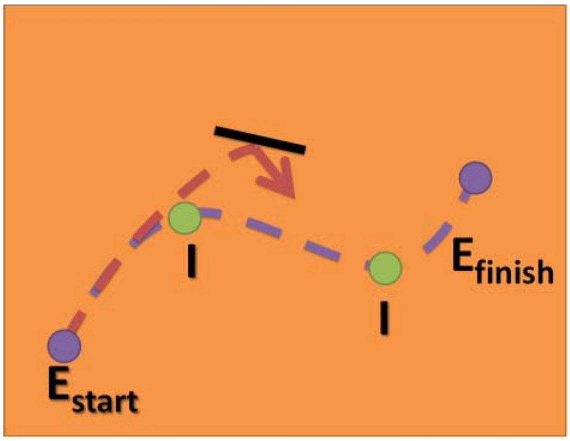

FIG 1 - Deflector's action.

This cost could be reflected in many ways, sometimes 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 yet, remembering, however, that what matters is the value generated and captured from the project (Figure 2), not just the cost as considered by Serpell and Alarcón (2003). 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.

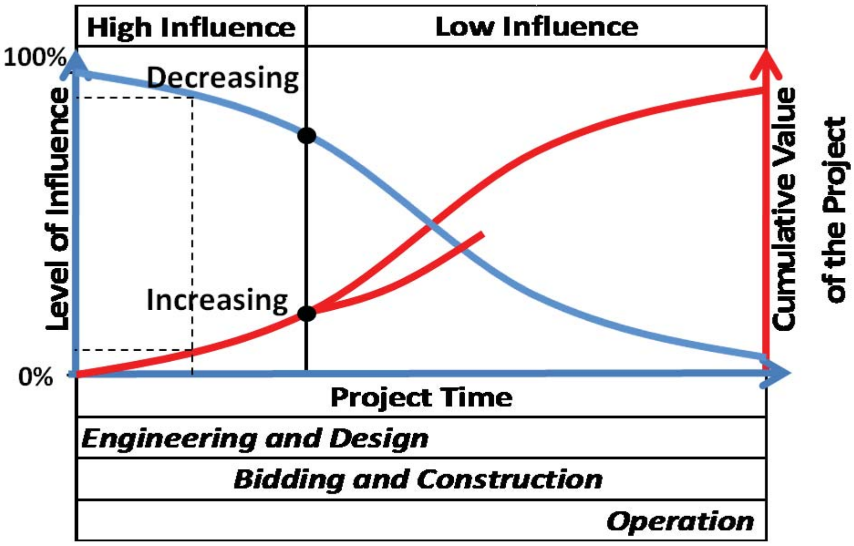

FIG 2 - Influence in the project time (Serpell and Alarcón, 2003).

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 lifetime 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 define the operational constraints applicable to a mining project. These are summarised below:

- 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 orebody, so segments allocated in different mineralisation zones can have different rates affected only by the 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 that 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 temporarily 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 net present value (NPV). Moreover, this could differentiate alternatives of design and, in some cases, it could 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 tunnel boring machine (TBM) and another 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 not feasible 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: this defines the continuity of tunnels and shows that for constructing one segment, all the tunnel segments that are behind it must be developed. In other words, it allows the machines to get to some point. Obviously this cannot be a variable and is supported in a given mine layout (Rahal and Smith, 2003).
- Operational precedence: this defines specifically which activities or segments must be done before another, but not in a physical way. It differs from the physical precedence because it is related to the mining system and makes the flow of ore to the surface possible (Figure 3). This category includes crushers, conveyors and load out bins. Consequently, like a reflection of the mining system, it depends on the operational precedence, what kind of mine should be created, or what kind of results should be obtained (Newman and Kuchta, 2007).

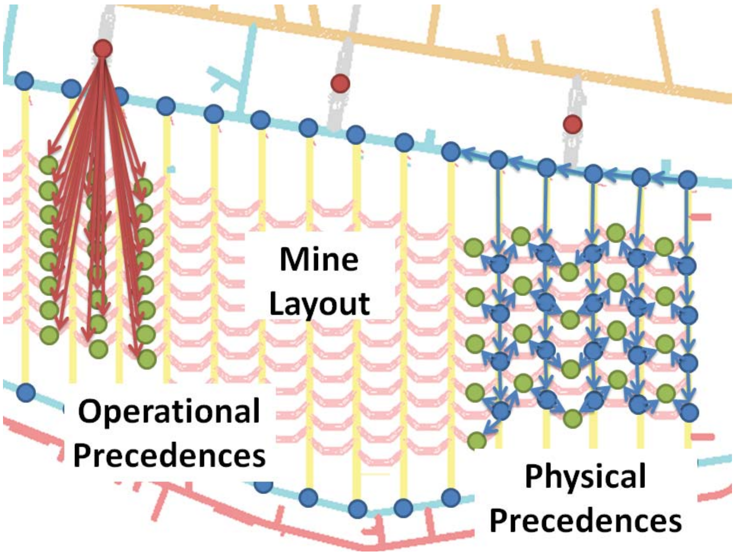

FIG 3 - Precedence.

- Production constraints: these state the parameters that have to be obeyed in 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 to the production level. Most importantly, it gives a space consistency in relation to the production activities (Rubio and Diering, 2004).
- 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 NPV, a set of time periods $\boldsymbol{t} = \mathbf{1, 2, \ldots}\ \boldsymbol{T}$ is considered, where $\boldsymbol{T} \in \boldsymbol{N}$ is the time horizon and the project life.

Activities and economic parameters

A set $\boldsymbol{A}$ of activities must be considered in order to fulfil the entire mine design. Then, for an activity $\boldsymbol{i} \in \boldsymbol{A}$, a cost or profit v_i^+ is considered for starting the activity $\boldsymbol{i}$, v_i^- for finishing the activity and $\boldsymbol{v_i}$ for developing the activity. In 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:

$$\boldsymbol{p_{it}} = \text{percentage of activity } \boldsymbol{i} \text{ developed at time – period } \boldsymbol{t}. \tag{1}$$

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

$$\boldsymbol{s_{it}} = \begin{cases} 1 \; activity\ \boldsymbol{i}\ has\ strated\ by\ time\text{ - }period\ \boldsymbol{t}, \\ 0\ if\ \ not. \end{cases} \tag{2}$$

$$\boldsymbol{e_{it}} = \begin{cases} 1 \; activity\ \boldsymbol{i}\ has\ not\ yet\ ended\ by\ time\text{ - }period\ \boldsymbol{t}, \\ 0\ if\ \ not. \end{cases} \tag{3}$$

Now, the status of an activity in the time can be determined as is illustrated in the Figure 4.

FIG 4 - Beginning and ending variables for a specific activity in the time.

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

$$\Delta x_{it} = \begin{cases} x_{i1} & t = 1 \\ x_{it} - x_{it-1} & t > 1. \end{cases} \tag{4}$$

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 $\boldsymbol{a} < 1$ that shows the time effect depending on the assumed risk, can be formulated as follows:

$$V = \sum_{t=1}^{T} \alpha^t \sum_{\boldsymbol{i} \in A} \left(\boldsymbol{v}_i \boldsymbol{p}_{it} - \boldsymbol{v}_i^{+} \Delta \boldsymbol{s}_{it} - \boldsymbol{v}_i^{-} \Delta \boldsymbol{e}_{it} \right) \tag{5}$$

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 6 shows that there is only one start time and one end time. Equations 7 and 8 show that to develop one segment, it has to be started and not yet finished, while, at the same time, the progress at any given period cannot be greater than 100 per cent of the total progress.

$$\Delta \boldsymbol{s}_{it} \geq 0, \quad \Delta \boldsymbol{e}_{it} \leq 0 \qquad (\forall \boldsymbol{i} \in \boldsymbol{A})(\forall \boldsymbol{t}=1,2,\ldots,\boldsymbol{T}) \tag{6}$$

$$\boldsymbol{p}_{it} \leq \boldsymbol{s}_{it} \qquad (\forall \boldsymbol{i} \in \boldsymbol{A})(\forall \boldsymbol{t}=1,2,\ldots,\boldsymbol{T}) \tag{7}$$

$$\boldsymbol{p}_{it} \leq \boldsymbol{e}_{it} \qquad (\forall \boldsymbol{i} \in \boldsymbol{A})(\forall \boldsymbol{t}=1,2,\ldots,\boldsymbol{T}) \tag{8}$$

$$1 - \boldsymbol{e}_{it} \leq \sum_{s \leq t} \boldsymbol{p}_{is} \qquad (\forall \boldsymbol{i} \in \boldsymbol{A})(\forall \boldsymbol{t}=1,2,\ldots,\boldsymbol{T}) \tag{9}$$

$$\boldsymbol{p}_{it} \leq \boldsymbol{v}_{max\, i} \qquad (\forall \boldsymbol{i} \in \boldsymbol{A})(\forall \boldsymbol{t}=1,2,\ldots,\boldsymbol{T}) \tag{10}$$

Additionally, Equation 9 says that to end an activity it is necessary to do 100 per cent of the labour, and finally Equation 10 sets the maximum development rate for all segments as was already defined.

Precedence

Precedence constraints, physical and operational, are modelled at the same time because they are not any different for the model. Then a set of requirements $\boldsymbol{P}(\boldsymbol{i})$ are considered for each activity $\boldsymbol{i}$, where one requirement can be a group of precedence activities. The idea is that activity $\boldsymbol{i}$ is ready to be started if there is a requirement $\boldsymbol{P} \in \boldsymbol{P}(\boldsymbol{i})$ that has been fulfilled, that is, each activity $\boldsymbol{j} \in \boldsymbol{P}$ has finished. Consequently, it may be possible for a specific activity to belong to more than one $\boldsymbol{P} \in \boldsymbol{P}(\boldsymbol{i})$ 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 Figure 5, which also shows that there are different precedence groups to start an activity.

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.

$$\boldsymbol{r}_{iPt} = \begin{cases} 1 \text{ activities in group } \boldsymbol{P} \in \boldsymbol{P}(\boldsymbol{i}) \text{ have been finished by time - period } \boldsymbol{t} \\ 0 \text{ if not} \end{cases} \tag{11}$$

Therefore, Equation 12 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 13 says that only if all the activities or segment related have finished can it mark that requirement '1'.

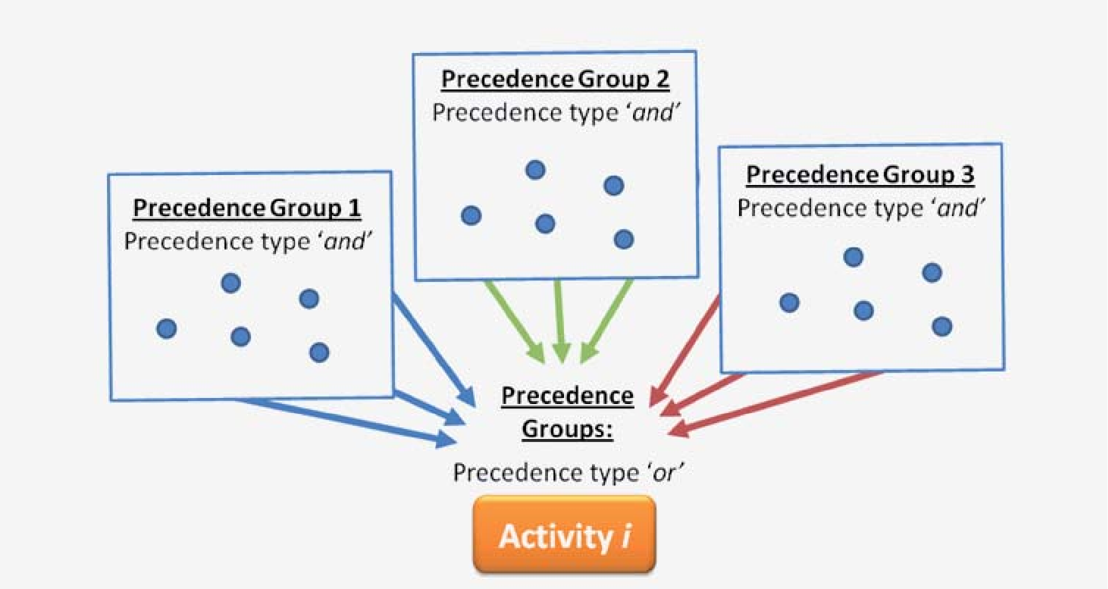

FIG 5 - Groups of precedence.

$$s_{it} \leq \sum_{P \in P(i)} r_{Pt} \qquad (\forall \boldsymbol{i} \in \boldsymbol{A})(\forall \boldsymbol{t}=1,2,\ldots,\boldsymbol{T}) \tag{12}$$

$$\boldsymbol{r}_{Pt} \leq 1-\boldsymbol{e}_{jt} \qquad (\forall \boldsymbol{i} \in \boldsymbol{A})(\forall \boldsymbol{P} \in \boldsymbol{P}(\boldsymbol{i}))(\forall \boldsymbol{j} \in \boldsymbol{P}) \tag{13}$$

Paths

It is worth noting that as a consequence of constraint (12), it is necessary to wait for a different period to start the next activity if its precedence constraint is correct. This could be solved if it frees the variable $\boldsymbol{s}_{it}$, nevertheless it has to be used carefully because it can become absurd when many consecutive activities are performed during the same period. Thus, one way to solve this dilemma is eliminating the Equation 8 related $\boldsymbol{e}_{it}$ and inserting a new type of constraint, where every activity can see not only its father, but all of their family tree, from the root to the leaf. So, for each activity $\boldsymbol{i}$, it considers a set of paths or familiar trees $\boldsymbol{F}(\boldsymbol{i})$, where one familiar tree or path is $\boldsymbol{F}$.

$$\sum_{i \in F} \frac{p_{it}}{v_{max\ i}} \leq 1 \qquad (\forall \boldsymbol{i} \in \boldsymbol{A})(\forall \boldsymbol{F} \in \boldsymbol{F}(\boldsymbol{i}))(\forall \boldsymbol{t}=1,2,\ldots,\boldsymbol{T}) \tag{14}$$

Resource consumption

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

$$\sum_{i \in A} \boldsymbol{c}_r^i \boldsymbol{p}_{it} \leq \boldsymbol{R}_t^r \qquad (\forall i \in \boldsymbol{A})(\forall r \in \boldsymbol{R})(\forall \boldsymbol{t}=1,2,\ldots,\boldsymbol{T}) \tag{15}$$

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 (Figure 6).

UNDERGROUND DEVELOPMENT SEQUENCER AND SCHEDULER

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 4.5.0, except for some previous steps when the data were being prepared and different supports for certain purposes were used, such as java or another mining package.

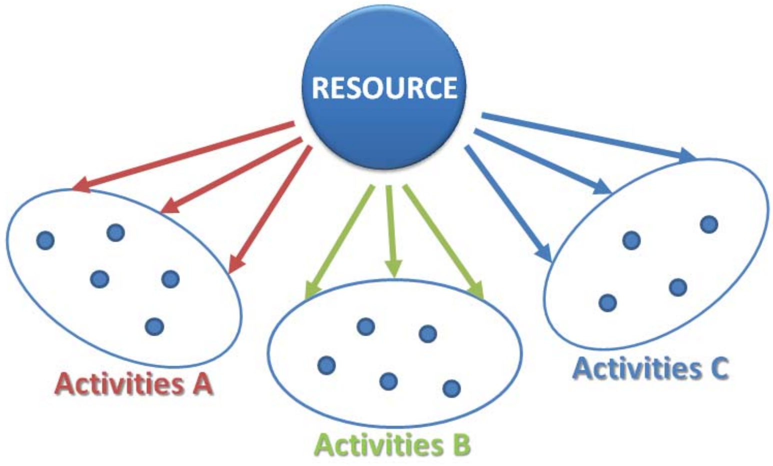

FIG 6 - Distributed resources to activities.

Implementation with extensible markup language (XML) interpretation

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 and length, illustrated like a cycle in the Figure 7 with details that permit an understanding of what it is happening in another step.

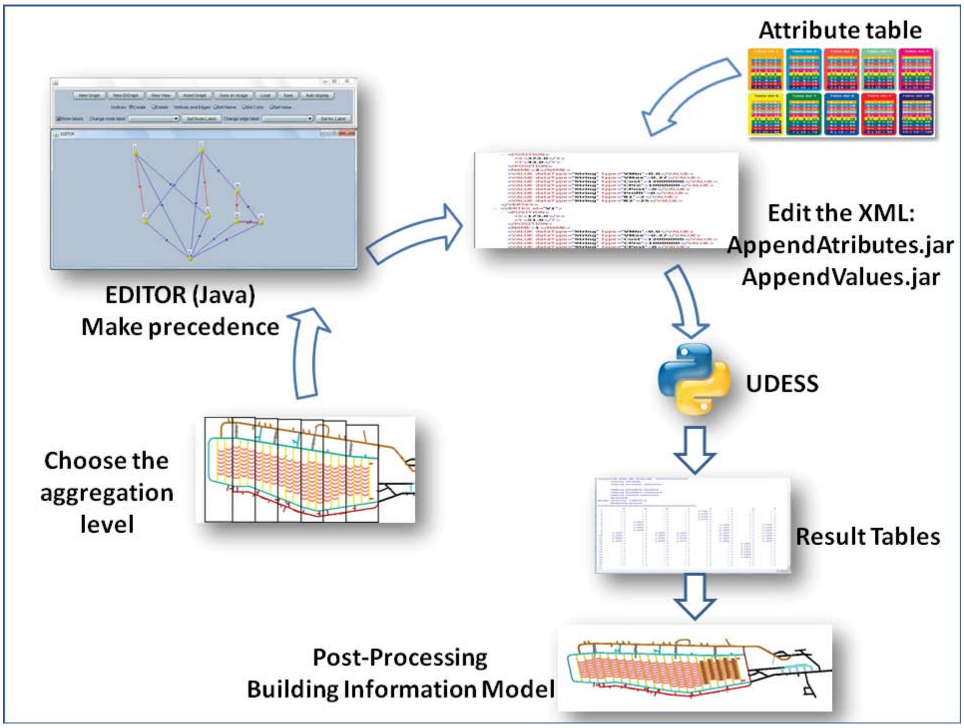

FIG 7 - XML implementation.

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 a 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 given 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 another strategy to prepare all data needed for the optimisation.

Implementation with mining package interpretation

There was an alternative view to enhance using a mining package. The idea is to facilitate the generation of activities' precedence in a clean way, not with a gantt chart, from a DXF file. Therefore the property that is looked for in commercial software is its ability to understand when two lines are connected and to export that information.

For this reason Mine2-4D was selected in this case. But it is important to understand that any other mining package could be used that has DXF reading capacity. 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 any gantt-chart management software, in this case from the Mine2-4D package, enhanced production scheduler.

Therefore, one important stage before optimising the sequence or schedule, for resolving the problem in a better way, is re-blocking the activities list. To do this, a simple programmed macro in Excel is implemented, it considers 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; it can keep all the information but in fewer quantities of activities, which is desirable for the optimisation.

Another change is that the production plan could come from an external analysis or be in the global list of activities to be optimised with the rest of construction and finally obtain the production plan as an outcome. When the production activities sequence is an input for the model, it has to be loaded with a different file (Figure 8 illustrate this cycle) and then UDESS is responsible for connecting the production activities with the development activities with precedence of physical type (already described), between them. This is done by searching for development activities close to a particular production activity. For example, in a block caving mine, it has to search which draw bell is the nearest from a given extract column, and if it finds it, the model understands that to extract the ore from that column, it must be done by the closest draw bell. Also it is worth noting that, in fact, this creates the possibility that some basic production unit isn't to be extracted or at least that delays their extraction, changing the optimal production solution and creating the need to revaluate it. When the production is an outcome, it is needed to include constraints of minimum or maximum tonnage for obtaining a full production plan for the processing plant.

Smart heuristics to process large volumes of information

For this kind of modelling and implementation, it is really difficult to take a big optimisation with a precision of half-month along the lifetime of a project, because it needs a great computational capacity. So, it is necessary to bring forward a smart heuristic to be able to solve the problem with UDESS in a real case study of a large caving mine, with a great amount of activities and periods to be considered. For this purpose, considering paths constraint, Equation 14, that corresponds to a representation of the sum of times it takes to finish each activity, it is possible to solve the optimisation with a large period length (Figure 9).

This means that all the optimisation is really a representation of multiple suboptimisations. First, solve the sequence and schedule yearly, for example, and then take each list of activities that did it in the year for another optimisation, imposing that every activity from that list must to be done at the end of the year to follow the global optimal. Finally, the results provide a detailed program where all the activities are scheduled to distinguish when it begins a new path.

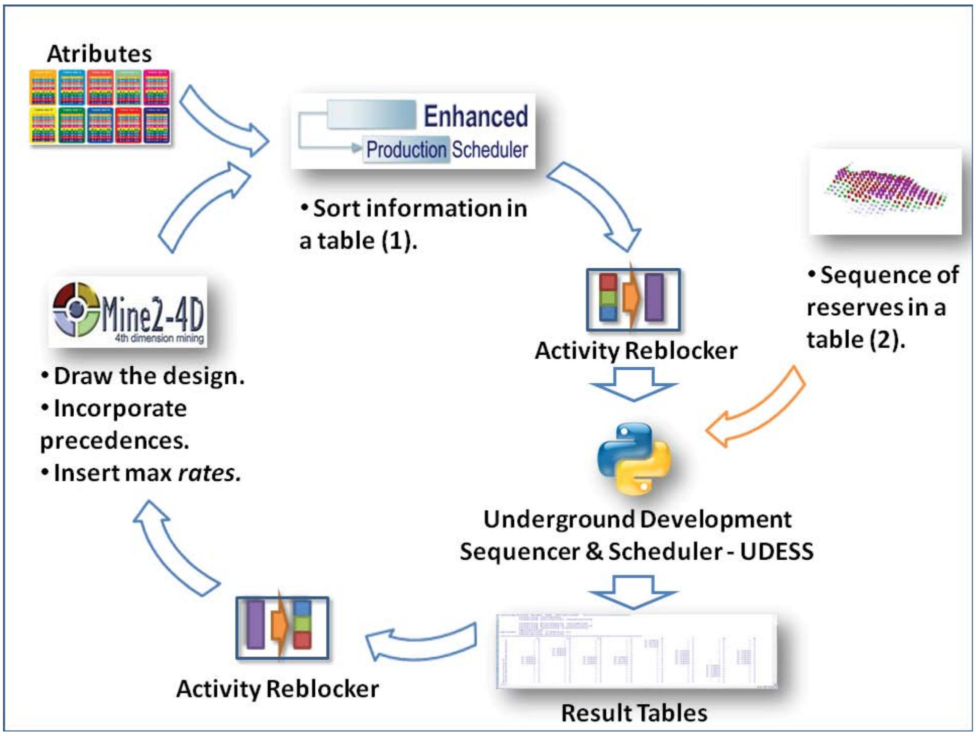

FIG 8 - Mining package implementation.

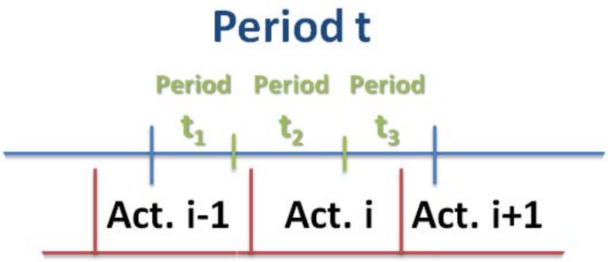

FIG 9 - Suboptimisation in a given period.

RESULTS AND DISCUSSION

Minimal underground mining designs were considered to test the model and implementation, which give hopeful results. They were performed considering a block caving and sublevel open stoping method.

For these first tests, in order to lighten the optimisation, it was considered that the construction of tunnels has a previously determined development direction. Therefore all the paths are discarded that are too long to build a small segment. This gives a bias to the outcome only when the mine is structured in a special way such as introducing several main accesses that are at similar distances, for example, and accordingly a gallery could be built from either side, a situation that is studied in the tests used due to the fact that they contain always a single access.

Without smart heuristic

Firstly, a Test A consisting of 106 activities was run with a time horizon of 60 monthly periods of a minimal sublevel open stoping (SLOS) mine. In this 106 activities are included the drifting development, stopes drilling and extraction of the ore to complete all the mine operations and the only equipment that is controlled is a Jumbo drill for drifting, a Simba drill for radial drilling and a LHD for ore production. The orebody consists of three vertical and parallel veins with three levels of stopes each. The main access is built through a ramp that connects the first body, there emerge drilling and production galleries for each of the three levels mentioned. Each level contains three stopes to be extracted each with different (and without a clear trend), profit. Next, a set of galleries are connected from the first body to the second orebody, trying to replicate the infrastructure exposed in the first case with the same characteristics and number of stopes. At last it connects with the third body in the same way (because it is adjacent to the second one), to complete the entire mine.

This test consists of putting a variation of drifting speed for development. As shown in Table 1, in some rates there is basically the same sequence (40 and 70 per cent of speed) extracting the first stope levels of each body and then deeper, preferring to develop at first the horizontal galleries and at the end the decline ramps. By contrast with a higher drifting speed, drastic changes appear, preferring to extract all the ore from a particular vein and then develop the drift to connect the mine with the following vein due to higher net profit. Finally, with a great drifting speed, it is possible to select specifically which stopes return higher value and eventually get a decreasing grade profile.

TABLE 1

Variation in the order of exploitation of stopes changing the drifting speed.

		Drifting speed				
		40%	70%	100%	130%	160%
Body 1	LOW 1	19	18	13	9	10
	LOW 2	18	17	12	8	9
	LOW 3	26	16	20	7	19
	MED 1	16	26	22	6	26
	MED 2	11	10	8	5	6
	MED 3	10	9	7	4	5
	HIGH 1	3	3	3	3	2
	HIGH 2	2	2	2	2	1
	HIGH 3	1	1	1	1	24
Body 2	LOW 1	23	21	16	18	14
	LOW 2	20	19	14	17	11
	LOW 3	24	24	19	16	17
	MED 1	17	15	25	15	21
	MED 2	15	14	11	14	16
	MED 3	12	11	9	13	7
	HIGH 1	8	8	23	12	20
	HIGH 2	4	4	4	11	3
	HIGH 3	7	6	27	10	27
Body 3	LOW 1	22	22	17	27	13
	LOW 2	21	20	15	26	12
	LOW 3	25	23	21	25	18
	MED 1	27	27	24	24	25
	MED 2	14	13	18	23	15
	MED 3	13	12	10	22	8
	HIGH 1	6	25	26	21	22
	HIGH 2	5	5	5	20	4
	HIGH 3	9	7	6	19	23

These observations are not at all trivial, since without this information the planner could have chosen only a forward direction of stopes, with no certainty that it is indeed the best business possible or at least showing it was a feasible plan.

Later as far as Test A is finished, with an efficiency of the activity reblocker of 40 per cent, 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 with large simplifications in relation to the galleries development, ie without excessive details, from an operation of a block caving mine, corresponding to the Test B.

For Test B a production target of 25 kilotonnes per day was imposed. Regarding that production operations will be with LHD equipment of seven cubic yards and the development is constructed by the conventional technique, which is to say, drill and blast. The mining system consists of a loader that brings ore from the 80 draw points of the mine lift to orepasses that connect to a transport level where the ore goes to the surface through a miner train.

This optimisation took 7.5 hours to finish in an Intel Core Duo 2.4 GHz with 3 Gb RAM with the following effects:

1. One was related with 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 developed before another for better economic results (Figure 10 shows this grouping of the activities). It should be noted that this effect doesn't respond just to an eventual levelling of resources, as if it happened, it would retain the sequence and it just would have extended its execution time.
2. The second effect was the loss of value while putting it under a tighter constraint, reaching a point where there wasn't any economically viable project (Figure 11). The situation expected under the resource constraint is that it can only decrease the value of the project by not allowing freeing resources to market as quickly as possible. That is, if there had been a better project proposal with fewer resources to saturation condition, it would have been delivered as a solution when the optimisation was performed. In fact, resources may be so restricted that there comes a time when the project cannot be done, this by any activity that cannot be completed because there are no instant resources for their development. For this reason, the final effect is related to insufficient resources and not the discount rate.

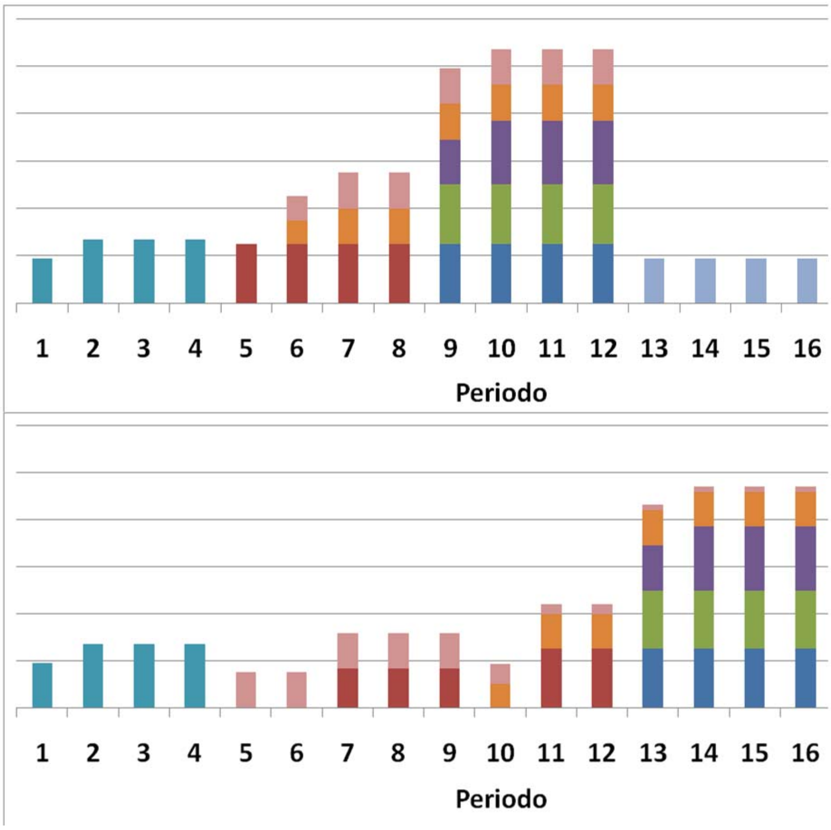

FIG 10 - Different schedules of mine sectors with varied optimised conditions.

With these two effects, it was demonstrated by using these tests in a simple way that there is a close relation between constructability and production. This would change the form of viewing a mine for operational purposes because it would require a different supply program or have to change the position of the machines between mine sectors. It is also important to mention that 'Test A' and 'Test B' do not incorporate in their designs any special peculiarity.

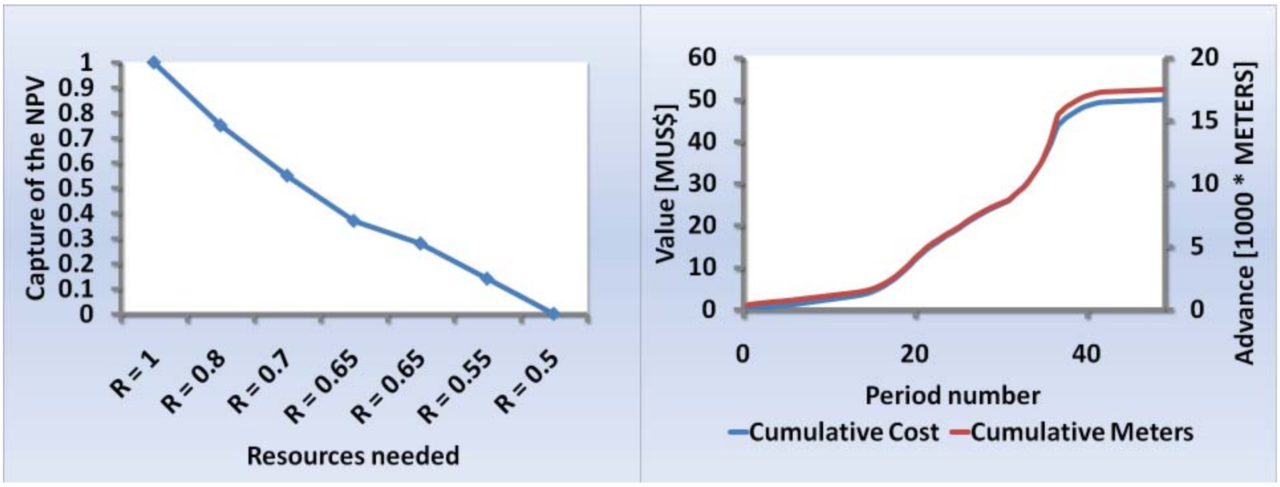

FIG 11 - Capture of the net present value with resources constraint and cumulative cost/metres.

Besides, the results show that the implementation works as expected, giving coherent outcomes with accepted shapes of S curve (Serpell and Alarcón, 2003) of cost and progress metres, showing an early effort to increase efficiency and improve their performance continuously until the system starts to run out, and therefore doesn't produce more even when spending the same amount of money. However, in this case two essential comments appear:

- it works at the limit of computer capacity: this implies that without a smart heuristic, more caution is required when choosing the aggregation level and time horizon, otherwise it will have to focus only on the long-term view, or alternatively short-term with a reduced set of activities; and
- solving this problem with paths constraint gives flexibility of solve with large period lengths, but at the same time as it is implemented currently, it is not possible to see exactly when it is doing each activity inside a given period.

With smart heuristic

The tests with the smart heuristic are made in order to compare the advantages obtained in contrast with the way already discussed above. Also, it is considered maintaining the same time horizon as previously, that is five years with a period length of a month.

The first comparison attempts to observe (under the same conditions of optimisation), how much the processing time would vary for different examples. Therefore a Test C is considered which consists of a part of the mine shown in Test A, leaving only one vertical vein as the body for extraction and therefore their activities are reduced to 60 to perform the operation. So, with a GAP, which is the tolerance on gap with the best objective, equal to 0.1 per cent, it took around 1500 seconds without the heuristic for the Test C and 30 seconds with it. Then it takes the Test A, with the same GAP, noting that took around 20 000 seconds without the heuristic and 370 seconds with it. Obviously was inspected to identify any differences between the final results of the two methodologies to verify that there are the same sequence and schedule. Finally, is possible to say that in both cases, there is a reduction of the processing time of approximately 98 per cent of the original. An impressive reduction in processing time creates great expectations because it requires only two per cent of the original time to get the same answer.

After the previous conclusion, it is desirable to view which are the changes that appear in the same Test A if it use a different GAP value.

In this manner, with a GAP of five per cent it took 73 seconds; with one per cent it took 134 seconds; but when it reduces the GAP value to 0.1 per cent it took only 370 seconds and with 0.01 per cent, just 390 seconds. While it is clear that this is only a test, lightening the problem reduces the GAP value, something which is always a concern. Despite the above, this apparent convergence on processing time for a lower GAP value is something that is not possible to generalise because it is directly related to the simple and small size of the studied problem.

CONCLUSIONS AND FUTURE WORK

It is essential to conciliate production and development plans and it must be a constant preoccupation for mine planners. From this point of view, the UDESS research creates an important advantage in the current mining industry because there are no optimisation tools like this for underground, long-term mine projects and it is clear that the computational capacity provides strong help when it is considered that a rapid evaluation tool for planners can give strong guides, and ultimately speed up calculations so that the planner can focus on other issues that are equally vital to the mining business. In this way, reducing the processing time to two per cent of the original time provides a huge potential. As a result of the analysis, the mine project is supported on a reasonable analysis, able to search the best economic alternative to develop and giving a schedule according to its specific resources and market requirements.

To put it briefly, the model proposed has unique characteristics that differentiate it from the other models available for development purposes. Firstly, it considers continuous variables, which means that unlike other methodologies if an activity starts, it does not necessarily have to be completed in a fixed time. Instead, an activity can be extended for several periods if it doesn't require urgency to be finished, or can be done as fast as possible if it is a critical activity any delay which will affect the whole project. In short, this model requires control of not only when an activity starts but also when it ends. Secondly, the precedence list is entered in a clean way, without additional and unnecessary constraints that could bias the problem as when extracted from a gantt-chart (Newman and Kuchta, 2007).

Finally, nowadays this new paths powerful constraint has been tested and shown to do several consecutive segments in the same period, making irrelevant the period length. It has already demonstrated the UDESS's ability to deliver consistent results and help in areas where before there was only the experience and skill of the engineer.

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