Methodology to Optimize and Sequence the Semiautomated Ramp Design in Underground Mining

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Abstract. There are few optimizing methodologies that may guide the process of ramp design in underground mining; they contemplate designing the accesses and then completing the mine exploitation schedule, which does not reflect the development costs in the NPV of the project and relies on the engineer´s knowledge.

The methodology presented in this paper focuses on the assisting the ramp design in underground mining using an optimization model that gives the operational costs associated with the accesses, during the development and the operation of the mine. Additionally, a sequence of construction is obtained as a complement of the design with a scheduling software. The methodology aims to obtain a design and sequence of the ramps and crosscuts configuration considering initial parameters that must be entered the optimization model, such as production levels, maximum slope, curvature, construction costs, transportation costs, among others. After applying the optimization model, the result is the identification of the points belonging to the ramp design, the ramp construction and operation sequence and the total cost associated with the project. This result must be refined using CAD software to obtain the final configuration. When this methodology is applied to a case study, a gold and silver mine exploited using the Bench & Fill method, the results show that the optimization model can replicate the design obtained by the pre-feasibility study of the project and provide additional design options that can reduce the total cost. The methodology provides operationally feasible solutions and can be used as a guide for the design of ramps in underground mining while reducing the time allocated to these tasks and delivering more than one design according to the initial parameters.

Keywords: Ramp Design, Optimization Model, Underground Mining.

1 Introduction

The mining industry market competitiveness forces the companies to continuously seek cost reduction strategies to improve the profit. On the other hand, there are few investigations about optimization of design of access routes in underground mining.

De Smith et al. [6] focused on the analysis of the gradient and on the curvature restrictions for road forms and lengths, to find optimal routes. The study contemplated three steps for the selection of the optimal route:

- initial alignment of the route subject to a preset range of gradient restrictions,
- horizontal smoothing of the route to find objectives of curvature and smoothness of horizontal route and
- vertical smoothing of the route to achieve similar objectives, with a minimum of cut/fill in the vertical plane.

Ghaffariyan et al. [7] developed a study to determine optimal path spacing, where the best solution found was based on a modification of the shortest path algorithm. The objective of the study was to apply a mixture of integral programming and network analysis to optimize the route.

Brazil et al. [1], [2], [3], [4] proposed the creation of an optimization tool that allowed obtaining the best alternative for the construction of ramps, shafts and tunnels to minimize the associated costs. Their work was based on Steiner's networks, where nodes are established that represent the places through which one must necessarily pass, given the design of the mine. These nodes must be joined by sections (ramp/gallery) that have associated costs corresponding to the development of the section and the cost for the transit of ore through it. Brazil et al. [5] developed some software to obtain the design of ramp using his algorithms.

In this paper, we present a methodology to assist the ramp design in underground mining, minimizing both development and operational costs. The methodology considers an optimization model that obtains an initial ramp design, which is subsequently, refined to arrive at the final configuration. A sequencing of ramps´ construction is generated using the UDESS software. The general sequencer model Universal Delphos Sequencer and Scheduler (UDESS) seeks to maximize the NPV of the scheduling, subject to resource constraints and precedencies, to generate a Gantt Chart of development of activities.

2 Optimization Model

The proposed methodology contemplates the creation of a mathematical model to solve a problem of minimization of costs of the ramp route, granting access to production levels via tunnels in a straight line called crosscut to extract the mineral. The mathematical model considers predefined starting point and the height for the connection between the crosscuts and the ramp.

The optimization model uses the following input parameters; the values of the parameters depend on the case to which the methodology is applied:

- a guiding form from which the ramp is generated, which defines the available space and the final form. A tolerance border is established for the location of the solution.
- the quantity and location of the access points to production levels, with the associated tonnage to be extracted from each level.

- the maximum tolerable slope in the construction of the ramp that the equipment can operate.
- development costs of ramps and crosscuts.
- operational costs of ramps and crosscuts.
- direction of the ramp (clockwise or counterclockwise).
- starting point of the ramp.
- cost of ventilation

In addition, a penalty is established in the optimization model whereas the curved sections generated during the modelling are "punished", because they are more complicated to construct operationally. These considerations were established after meetings with experienced consultants.

Similarly to the design of ramps in open pit mines [8], the methodology consists of precomputing shortpaths at block level for each level of the mine within a predefined boundary and using the mathematical model to determine which are the best shortpaths to assemble to generate the full ramp.

The nomenclature for the proposed mathematical modelling is as follows:

B	the block model
K	the maximum level at which the ramps can begin
B_k	the set of blocks of level $k, k \in \{0,1,\ldots,K\}$, level 0 is lower level, K is ramp top level
b_{startk}	the starting block of the ramp
F	the defined boundary of blocks where ramps can pass
E	the set of the access points
E_k	the set of the access points for the production level k
$\hat{k}_e$	the level of the connection of the crosscut starting from e with the ramp
$\underline{\hat{k}}$	the minimum level for the connection of the crosscut, that start from the lower access point with the ramp ,
I_k	the set of indexes i of all precomputed paths of level k
s_k^i	the ith precomputed path of level k
o_k^i	the first block of s_k^i
f_k^i	the last block of s_k^i
$b_{e,k}^i$	the block of s_k^i nearest to the access point e
l_k^i	the approximation of length of s_k^i
$l_{e,k}^i$	the approximation of length of $(f_k^i, b_{e,k}^i)$
c_k^i	the value equal to 1 if s_k^i is a curve, else equal to 0
C_{H1k}	the haulage cost of all the mine production for one meter of ramp that must pass on level k
C_{H2e}	the haulage cost of the production of the access point e for one meter of ramp
C_{Te}	the haulage cost of the production of the access point e for one meter

of crosscut

C_{RD}	the cost of development of 1 meter of ramp
C_{CD}	the cost of development of 1 meter of crosscut
C_{VD}	the cost of ventilation of development of 1 meter of tunnel
V_T	the cost of ventilation that corresponds to the haulage
P_{RD}	the penalization of one meter of curve tunnel development

The variables of the problem are defined as follows:

$$y_b = \begin{cases} 1 & \text{if block } b \text{ belongs to ramp,} \\ 0 & \text{otherwise.} \end{cases}$$

$$x_k^i = \begin{cases} 1 & \text{if all blocks of level k of } s_k^i \text{ are part of the ramp of level } k \\ & \text{and } f_k^i \text{ is the first block of the ramp of level } k-1, \\ 0 & \text{otherwise.} \end{cases}$$

Domain definition of variable y is F, domain definition of index k of variable x is {1, 2,...,K}, domain definition of index i of variable x is Ik

Therefore, the Single Ramp Underground Design Problem (SRUDP), can be formulated as follows:

$$\begin{aligned} (SRUDP) \quad min \sum_{k=1}^{K} \sum_{i \in I_k} & \left((C_{RD} + C_{VD}) \cdot \left(1 + P_{RD} \cdot c_k^i\right) + C_{H1k} \cdot (1 + V_T) \right) \cdot l_k^i \cdot x_k^i \\ & - \sum_{e \in E} \sum_{i \in I_{\hat{k}_e}} C_{H2e} \cdot (1 + V_T) \cdot l_{e,k}^i \cdot x_k^i \\ & + \sum_{k=1 \,|\, \exists e \in E_k}^{K} \sum_{i \in I_k} (C_{CD} + C_{VD} + C_{Te} \cdot (1 + V_T)) \cdot \left\| eb_{e,k}^i \right\| \cdot x_k^i \end{aligned} \tag{1}$$

$s.t.$

$$\sum_{i \in I_k \,|\, f_k^i = o_{k-1}^j} x_k^i \geq x_{k-1}^j \qquad (\forall k > 1, \forall j \in I_{k-1}) \tag{2}$$

$$\sum_{i \in I_k} x_k^i \leq 1 \qquad (\forall k \geq 1) \tag{3}$$

$$x_k^i \leq y_b \qquad (\forall k \geq 1, \forall b \in s_k^i) \tag{4}$$

$$\sum_{i \in I_k \,|\, b \in s_k^i} x_k^i \geq y_b \qquad (\forall b \in F) \tag{5}$$

$$\sum_{i \in I_K \,|\, o_K^i = b_{start}} x_K^i \geq 1 \tag{6}$$

$$\sum_{i \in I_{\underline{\hat{k}}}} x_{\underline{\hat{k}}}^i \geq 1 \tag{7}$$

$$x_k^i = 0 \qquad \left(\forall k < K, \forall i \in I_k \,\middle|\, \left\{ s_{k+1}^j \,\middle|\, f_{k+1}^j = o_k^i \right\} = \emptyset\right) \tag{8}$$

The objective function (1) minimizes the overall development and operational costs of ramp sections in a level, crosscuts and ramp connection between levels.

Constraint (2) ensures the connectivity between ramp paths. Constraint (3) states that there is at most one ramp per level. Constraint (4) ensures that for each chosen path, all blocks in the path are part of the ramp. Constraint (5) states that ramp block belongs to an elected precomputed path. Constraint (6) states that the ramp will start from the defined start block. Constraint (7) forces the existence of a ramp to connect the lower crosscut. Constraint (8) prevents a no connected path from being an eligible path.

SRUDP model is equivalent to a shortest path problem to minimize the function cost (1) instead of the length of paths. The graph of connection of all precomputed paths is constructed. Each arc is associated with the cost that corresponds to the development of this tunnel part and the corresponding operational cost. The operational cost includes the haulage cost of material that goes through the arc, considering the crosscut development and operational costs, if the level of path corresponds to a fixed connection height $\hat{k}_e$. The shortest path problem can be solved very fast; however, the proposed methodology is addressing a more general problem because the optimal height of the crosscut connections with the ramp is not known in advance. To solve this more general problem, a heuristic approach that tries different heights of connection starting from horizontal crosscuts was made to approximate the optimal ones. The heuristic keeps the ones that improve the cost function starting from the higher crosscut, considering only a feasible connection boundary and preventing the intersection of crosscuts. The heuristic iterates while the value of the objective decreases.

3 Methodology and Performance

The procedure to use the heuristic optimization model requires a block model of the workspace, where the access points to production levels are identified and the shape and working space for the design of the ramp are defined. This block model must be in a text file format separated by tabs. The input values are defined as: costs, slope, tonnage to be extracted from production levels, direction, start point, and penalty of arcs.

To execute the modelling code, a server with a Xeon processor E5-2660v32 @ 2.6GHz. 128 GB RAM with a CPU that has 20 threads was used. The execution time is approximately 2 minutes, although this depends on the amount of data within the block model. The outputs are the approximate total cost of the design and the points where the ramp passes. When these points are viewed, they are blocks, whose size varies depending on the resolution used. This design contemplates the original dimensions of the final design, its costs and the tonnage associated with the development. This solution must be refined by the engineer in charge of the design, to transform the points into a triangulation that represents the real section of the gallery, using mining CAD software. The data flow of the methodology is summarized in Figure 1.

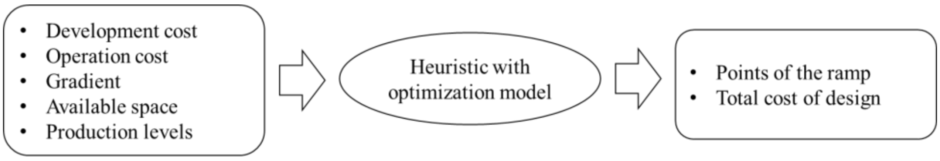

Fig. 1. Flow chart of methodology.

4 Case Study

A case study of a gold and silver mine operated by Bench & Fill was undertaken. The data used in this section was provided by a confidential prefeasibility study made in 2014, which includes from geostatistical study until final economic analysis.

The mine had two main sectors and three exploitation zones: Y east mine, Y west mine and V mine. Production levels were separated by 12 meters vertically. Some levels had a principal drift to connect crosscuts to access the extraction galleries, while in other levels, it was possible to access directly without using the drifts.

The methodology to design ramps was used in three zones: Y east, Y west lower and Y west higher. The objective of the case study was to replicate as much as possible the original designs of the prefeasibility study and, therefore, each zone was considered independently of the others, it was expected to use the same space available and respect a gradient 13% proposed in the report of the project.

Y east zone had 26 production levels, but the design had to reach an access to 13 main drift because in these levels the drift system was implemented. In Y west lower zone there were 11 drifts to access; therefore, there were 22 production levels. Finally, Y west higher zone did not have the drift system; there were 15 production levels to access directly.

4.1 Ramp Design Result

The results obtained with the application of the new methodology are showed in Table 1. Because there were three zones, the methodology was used three times and the time for execution required was about three minutes for each zone.

Table 1. Developed meters and total cost for each zone.

Zone	Y east	Y west lower	Y west higher
Long developed ramp [m]	1,099	1,136	1,455
Long developed crosscuts [m]	979	522	443
Total cost [MUSD]	10.8	10.5	5.5

Figure 2 shows a comparison between designs obtained using the proposed methodology and designs obtained by prefeasibility study. In general, the designs are very similar in the three zones. The main difference is in Y west lower zone, where the upper half is different because the prefeasibility study design had two values of gradient: 13% and 15%, while the design obtained by methodology used a gradient of 13% only.

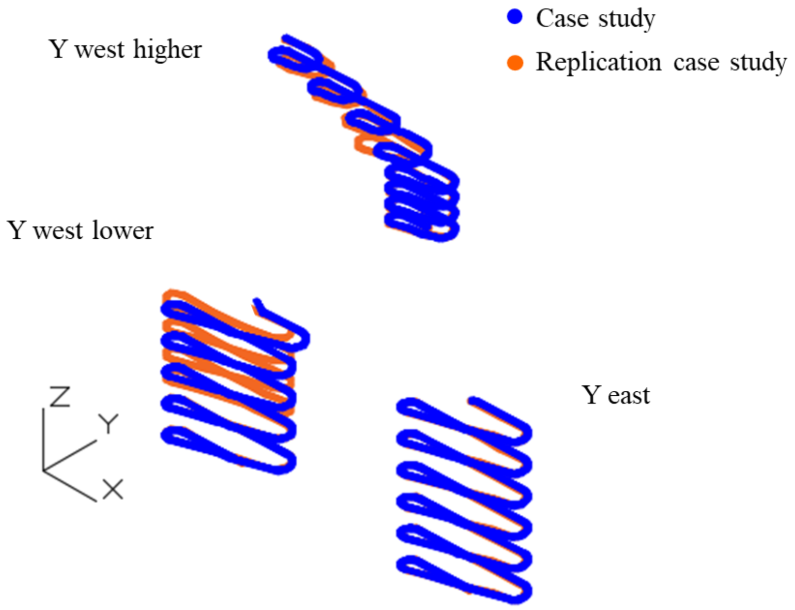

Fig. 2. Comparison of designs.

4.2 Sequencing Result

The UDESS tool was used to accomplish the sequencing of ramp and crosscuts construction and extraction of ore from production levels, through a maximization of NPV. Three types of activities were defined: ramp sections, crosscut sections and production levels, which had associated revenues and costs. In addition, three types of restrictions were set: maximum tonnage extracted per period, effective hours of work and availability of equipment for construction.

The sequencing of the three zones was considered as a single problem in UDESS and each sector was considered as independent of each other. The exploitation of production levels was from the bottom up. The problem considered by UDESS consisted of 467 activities and 728 precedencies and the execution time was 4.6 hours. The result yielded a NPV of 1,041.8 MUSD, 13 years of ramp and crusher construction and 18 years of ore extraction, as shown in Figures 3 and 4.

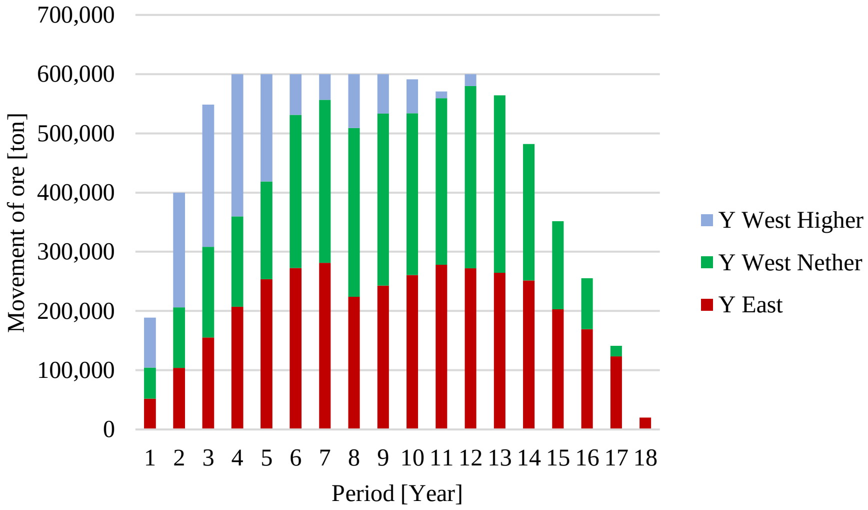

Fig. 3. Tonnage extracted per year obtained from UDESS.

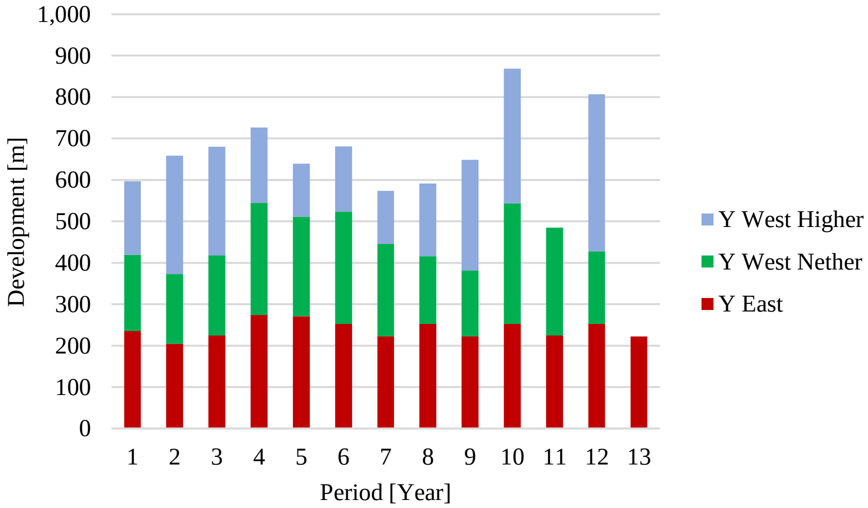

Fig. 4. Development per year obtained from UDESS.

In general, the results are consistent with the maximum extraction rates. The ramp-up lasted three years and the ramp-down four years, which are reasonable times for the scale of the project. The progress of development of ramps and crosscuts was related to the opening of production levels, which had precedence among them to extract the ore from the lower levels as a priority.

5 Conclusions

The designs made in the case study allowed to verify that the proposed model is capable of replicating the designs of the engineering study, which proves that this tool can provide feasible solutions for the industry.

The times required for the execution of the heuristic are prudent, between one to three minutes, depending on the case study. The complexity lies in a good establishment of the ramp guide form according to the conditions of each case.

On the other hand, the heuristic with optimization model is capable of delivering solutions that can assist in the design of ramps, facilitate the work of the engineer and deliver options with more objectivity.

For the construction sequencing, it is observed that the times needed are linked with the dimensions of the deposit and the amount of infrastructure needed. This scheduling is a good complement of ramp design because it allows to verify the times of the project from initial stages.

As future work, the construction of a heuristic which can obtain the ramp and crosscut design and, in addition, the sequencing of construction thereof, maximizing the NPV of the associated project, is proposed. The idea is to generate designs that involve some aspects of the production to include, from the beginning of the project, the costs of the infrastructure necessary for the operational stage.

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