# Semi-Automatic Generation of Ramps in Open Pit Mining Using Mathematical Programming

**Cristopher Díaz, Andrés Parra, Pierre Nancel-Penard and Nelson Morales**
*Delphos Mine Planning Laboratory, Department of Mining Engineering and Advanced Mining Technology Center, Universidad de Chile*

## ABSTRACT

The design of ramps in open pit mines is a key step in the mine planning process in which the economic envelopes obtained by optimization techniques and algorithms are transformed into operational volumes (phases) that are suitable for extraction. Despite the existence of tools that aid in the design of ramps, this process remains very complex and time consuming. This implicates few opportunities to explore different arrangements and, thus the quality of the resulting design depends on the engineer's expertise and availability of time.

In this paper, a mathematical model is presented which allows a semi-automatic generation of the ramp design from the economic envelope of a pushback at a block level. The inputs for this model are a valuated block model and design constraints, such as, ramp width, inter-ramp slope angle, ramp slope and others, generating a block path that allows to achieve the maximum value of the resulting envelope.

Different experiments were undertaken by modifying the input parameters, for instance, the starting block, rotation (clockwise and counter clockwise) and limits of the search domain of the ramp, with the purpose of generating a guide to assist in the design of the ramps achieving maximum profit. Using this guide, the final pit design was generated allowing a comparison with the current state-of-art in ramp design for open pits.

The results indicate that the methodology assisted by the mathematical model obtains very similar values in relation to the current state of the art, for the study case, however, it is possible to conclude that this tool provides greater robustness to the planning process; allowing to analyze different design scenarios in a limited period, ensuring an optimum economic design.

## INTRODUCTION

Within long-term mining planning, the operational design of phases consists of incorporating access to each phase and the connection between them, to obtain the largest possible part of available reserves, subject to the trade-off between extracting more ore and the associated waste, or less waste and associated ore. This certainly has an impact on the economy of the mining project.

Accesses to extract and transport the material from inside the pit are made by ramps which allow the movement of the mining equipment. Currently, it is one of the subjects of which little is written in the mining literature; because planners do not have a definitive methodology for design (Hustrulid, Kuchta & Martin, 2013). However, a good design of the ramp geometry will be one that delivers the greatest economic benefit (contained in pit design reserves with ramp), fulfilling all geometric specifications imposed by geotechnics (Thompson R., 2011).

In truck-based transport systems, the network of transportation roads in mines is a critical and vital component of the production process, since truck costs can account for up to 50% of the total operating costs incurred by an open pit mine (Thompson R., 2011, Atkinson, 1992), and any savings generated by better design and management of ramps directly benefits the mining company, as a reduction of cost per metric ton of material transported.

Under the current state of art, ramp design presents difficulties. First, the task requires a lot of work, skills and information, so, the opportunities to test different scenarios, or check the robustness of the solutions are limited. Secondly, even if the obtained solution is the best possible, much time is required to create a design, which means that the task is very expensive. Finally, the fact that design is generally a manual process, it can be supported by computer-aided design (CAD) software, and that the operating phases do not necessarily coincide with the original pushbacks, since the algorithms that generate them do not consider elements of design such as operative spaces and ramps, there is no guarantee that the resulting benefits will be the best.

Considering the mentioned improvement opportunities, will there be the possibility of introducing a mathematical tool that maximizes the value of the mining project, through a guide in the design of ramps? In this paper, we seek to take a first step towards generation and implementation of a tool of this type.

## CURRENT STATE OF ART IN THE RAMP GEOMETRIC DESIGN

The geometric design, is responsible for the layout and alignment of the ramps, both horizontally and vertically (Thompson & Visser, 2006). There are many questions that must be answered at the moment of locating the ramps, among the main ones: Where will the ramp surface go? Should there be more than one means of access? Should the ramps be external or internal to the pit? Should they be temporary or semi-permanently? Should the ramp spiral around the pit? Does it have switchbacks anywhere? How many roads must the ramp have? What should be the ramp slope? What should be the direction of traffic flow? and is the trolley assist a viable consideration for trucks?

Once these and other questions are answered, a series of steps are followed to geometrically design the ramps in the wall of the mine slope, both inside and outside the limits of the optimum pit. At this stage the planner encounters a trade-off between compromising an ideal design and what mining slope geometry and economy will allow (Thompson R., 2011; Atkinson, 1992).

The problem between the amount of ore and waste to remove or stop extracting is inevitable at the moment of incorporating the ramp in the operational design (Hustrulid, Kuchta, & Martin, 2013), and can be seen in the schematic of Figure 1. In this case the ramp passes through an intermediate bench reference, which can be selected based on some criterion such as choosing the bench with greater contribution of fine to the project, or the one that allows maximizing the final flow of the project, which will result in a smaller reduction of the horizontal extension in the lower benches and a smaller increase of the horizontal extension in the upper benches; compared to the case of choosing a reference bench in an area more top or bottom of the pit. Thus, generally there is a pit design with ramps having greater overall angles regarding the optimal final pit (Atkinson, 1992).

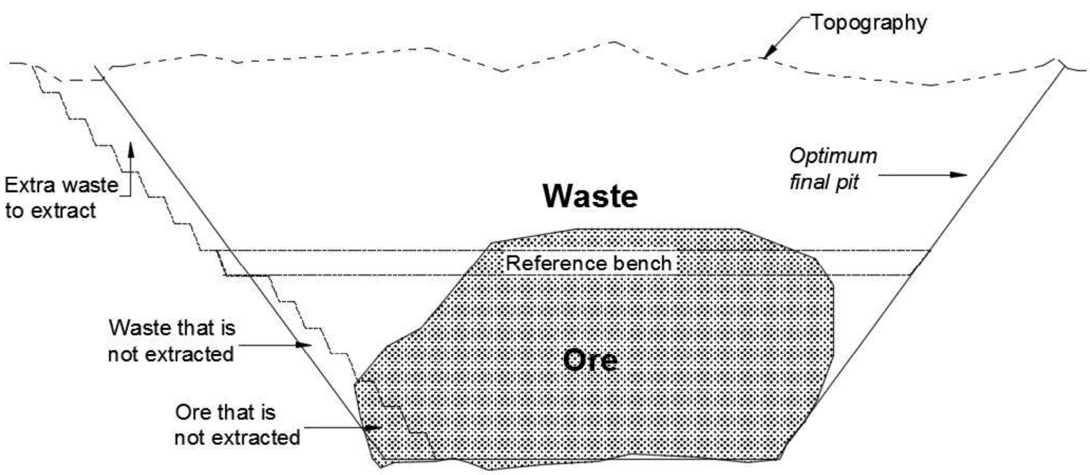


**Figure 1** Ramp integration in the operational design of a pit

As shown in Figure 1, for the design case below the reference bank, adding a ramp to the pit consists of moving the wall into the pit and losing some material, usually ore, resulting in a design within the limits of the original pit (Hustrulid, Kuchta, & Martin, 2013). The design of this type of ramp starts at the pit bottom.

In the opposite case, the design above the reference bank, adding a ramp to the pit consists of moving the wall out of the pit and removing some additional material, generally waste, resulting in a design outside the boundaries of the original pit (Hustrulid, Kuchta, & Martin, 2013). The process is like the previous case, however, this time it starts at the crest of the highest bank. A decision must be made regarding the entry point for the ramp as well as the direction. The location of crusher and dump are the first factors in the selection of the ramp entry point.

## MATHEMATICAL MODEL FOR GEOMETRIC DESIGN OF OPTIMAL RAMPS AT BLOCK LEVEL

This static model was developed to model the ramps of an open pit mine and all the blocks that must leave by the mining design, solving a linear mathematical optimization problem whose objective function is to maximize the total profit. It is not prevented that more blocks are removed than necessary to build the ramp. Also, in this first modelling effort, switchbacks are not allowed, but a ramp width of more than one block is allowed. The model is implemented as two computer programs for its execution, the first for constraints generation and the second, which uses the results of the first, for the construction of a pit with ramp at block level. For the execution of these codes a block model file is required, with attributes of spatial coordinates, mass, law of the metal of interest, a valuation and a binary envelope variable (one if it is inside the envelope, zero if not), for each of the blocks.

For the calculation of the constraints a text document is created that considers the inter-ramp angle constraints, which act throughout the mining slope, as well as global angle constraints, only for a certain range of levels in height, so that the two angles are respected. It is possible to consider more than one global angle, defining its ranges in the slope rosette. It should be considered that such restrictions correspond to vertical constraints. As result of this step, a text document is obtained, with constraints information for each block.

The computer program for the construction of pit with ramp, uses the output file of constraint, the block model and a text document with the technical parameters to be used, such as: variable frontier of the pit (as possible domains of search of possible paths between consecutive levels, in the outer block of the ramp for each level), direction of rotation of the ramp, the ramp slope, width ramp (is modeled as horizontal constraints), starting block (at the uppermost level), Gurobi parameters (optimization software used to solve the mathematical problem) and a series of mathematical parameters, typical of a problem of this magnitude. As result, a text document is generated, which adds attribute columns to the block model, such as frontier layers, ramp design and pit design with ramp.

The following definitions are needed to understand the model. $\mathcal{B}$ is the set of blocks, $\mathcal{B}_k$ the set of blocks of level $k$, $\mathcal{B}_b$ the set of predecessors by slope angle of block $b \in \mathcal{B}$. The $p_{b,k}$ value is obtained by extracting and processing block $b$ of level $k$. $\mathcal{PIT}$ is the set of blocks that are inside the pit by which the ramps must be built to be able to remove the blocks.

$\mathcal{F}$ is the set of possible blocks for ramps, these are blocks that are in the cartesian space near $\mathcal{PIT}$ by the external frontier and blocks in $\mathcal{PIT}$ near the outside of the pit by the internal frontier. $\mathcal{F}_k$ is the set of possible blocks for the ramp at $k$ level. $\mathcal{F}_k$ is included in an inner and outer frontier to the pit. $\mathcal{P}_{b,b',k}$ is the set of $\ell$ blocks belonging to a path between a $b$ block in $\mathcal{F}_k$ and a $b'$ block in $\mathcal{F}_{k-1}$ such that all the $\ell$ blocks which are not extremities of the path, are in $\mathcal{F}_k$. For $\mathcal{P}_{b,b',k}$, in case of a ramp width of more than one block, only the paths on the outside of the ramp are considered. $b$ block is an access to $k$ level, $b'$ block is an access to $k-1$ level. The accesses are considered accesses at the outside of the ramps.

$\mathcal{O}_{b,k}$ is the set of possible accesses by the $k-1$ level considering that block $b$ is the access of level $k$. It is the set of $b'$ blocks of $\mathcal{F}_{k-1}$ such that there is at least one non-empty $\mathcal{P}_{b,b',k}$. $K_{max}$ is the maximum level $k$ where there are $b$ and $b'$ blocks such that $\mathcal{P}_{b,b',k}$ is not empty. It is the maximum value that can take the $k$ level in all constraints of the model. $K_{min}$ represents the minimum $k$ level where there are $b$ and $b'$ blocks such that $\mathcal{P}_{b,b',k-1}$ is not empty. $\mathcal{H}_{b,b',k}$ is the set of blocks, at the same $k$ level as $b$ block, which must be drawn to obtain a ramp of a given width for the set of $\mathcal{P}_{b,b',k}$ blocks including $b$ access. These are on the inside of the ramp. $\mathcal{H}$ is the set that is the union of all $\mathcal{H}_{b,b',k}$ for all $\mathcal{P}_{b,b',k}$ paths.

The binary variables are defined as $y_{b,k}$ equal to one if block $b$ of level $k$ is extracted, $o_{b,k}$ equals one if block $b$ is an access ramp at level $k$. Binary variable $x_{b,k}$ equals one if block $b$ belongs to the ramp of level $k$. Binary variables $e_{b,k}$ equals one if $b$ block belongs to a path on the outside of the ramp of $k$ level. Binary variables $x_{b,b'}$ equals one if there is a ramp on the outside that goes from $b$ access to $b'$access. C is a positive constant.

Next, the model (CW-RAMP) (constrained width ramp) modelling ramp widths greater than one block is presented.

$$(CW-RAMP) \qquad \max \sum_{k\geq K_{min}, b\in\mathcal{B}_k} p_{b,k}y_{b,k} - C_{r_{b,k}} \tag{1}$$

$$s.t. \qquad \sum_{b\in\mathcal{F}_k} o_{b,k} = 1 \qquad \forall k \geq K_{min} \tag{2}$$

$$\sum_{b'\in\mathcal{O}_{b,k}} o_{b',k} \geq o_{b,k} \qquad \forall k \geq K_{min}, b \in \mathcal{F}_k \tag{3}$$

$$e_{b,k} \geq o_{b,k} \qquad \forall k \geq K_{min}, b \in \mathcal{F}_k \tag{4}$$

$$o_{b,k} + o_{b',k-1} \leq 1 + x_{b,b'} \qquad \forall k \geq K_{min}, b \in \mathcal{F}_k, b' \in \mathcal{O}_{b,k} \tag{5}$$

$$x_{b,b'} \leq e_{\ell,k} \qquad \forall k \geq K_{min}, b \in \mathcal{F}_k, b' \in \mathcal{O}_{b,k}, \ell \in \mathcal{P}_{b,b',k} \tag{6}$$

$$\sum_{b\in\mathcal{F}_{K_{min}}} e_{b,K_{min}} \leq 1 \tag{7}$$

$$x_{b,b'} + e_{\ell,k} \leq 1 \qquad \forall k \geq K_{min}, b \in \mathcal{F}_k, b' \in \mathcal{O}_{b,k}, \ell \in \mathcal{F}_k \setminus \left\{\mathcal{P}_{b,b',k} \cup \{b\}\right\} \tag{8}$$

$$r_{b,k} \geq e_{b,k} \qquad \forall k \geq K_{min}, b \in \mathcal{F}_k \tag{9}$$

$$y_{b,k} \geq r_{b,k} \qquad \forall k \geq K_{min}, b \in \mathcal{F}_k \tag{10}$$

$$y_{b,k} \leq y_{b',k'} \qquad \forall k \geq K_{min}, b \in \mathcal{PIT}^C \cup \mathcal{H} \cup \mathcal{F}_k, b' \in \mathcal{S}_b \cap \{\mathcal{PIT}^C \cup \mathcal{H} \cup \mathcal{F}\} \tag{11}$$

$$x_{b,b'} \leq r_{\ell,k} \qquad \forall k \geq K_{min}, b \in \mathcal{F}_k, b' \in \mathcal{O}_{b,k}, \ell \in \mathcal{H}_{b,b',k} \tag{12}$$

$$r_{b,k} + y_{b',k-1} \leq 1 \qquad \forall k \geq K_{min}, b \in \mathcal{F}_k, b' \; justo \; debajo \; de \; b \tag{13}$$

$$y_{b,k} = 0 \qquad \forall k \geq K_{min}, b \in \mathcal{PIT} \setminus \{\mathcal{H} \cup \mathcal{F}\} \tag{14}$$

## METHODOLOGY

The work methodology begins with the exploration of the block model that defines the deposit. Then the stages of optimum envelope selection, nested pits, economic evaluation and phase definition were developed; assuming an angle and overall height of slope, and selection of optimal final pit.

A methodology for a geometric design of ramp assisted by the mathematical tool was proposed, following four stages: first, construction of access to the optimal envelope, at the block level, using the mathematical tool. Second, the generation of new envelope (iteration) with angle values and overall height of slope, obtained from pit ramp from the previous step.

Third, construction of the accesses to the new optimal envelope, at the block level, using the mathematical tool. Fourth, construction of final pit with ramp with the help of CAD-type design software, using as a designing guide the results of the previous stage.

By using the methodology with the mathematical tool, a series of experiments is generated varying the search domain, starting point and direction of rotation of the ramp. In parallel, the final pit construction with ramp was generated to the optimal (original) envelope, using current state-of-art, with the help of CAD-type design software. Finally, a technical and economic comparison was made, between the operations with both methodologies described for the design of ramps.

## STUDY CASE

The study case used a block model that contains copper as element of economic importance. The model has uniform blocks of 10 [m] in each dimension, and an extension of 570 [m] wide, 760 [m] long and 260 [m] high. There are plant and dump destinations, to which the extracted material can be sent.

It has the following constant input data: a density of 2.6 [t / m3] for all blocks, a flat topography that intersects the model at the 2,205 [m] level and optimum material movement from the 8.4 [Mtpa] mine. By having a fixed volume blocks of 1,000 [m3], Its tonnage will have the same value of 2,6 [kt].

The study case was developed considering the following economic scenario: price metal 2.0 [US $ / lb], cost refining 0.65 [US $ / lb], metallurgical recovery 85 [%], mine cost 1.8 [US $ / ton], cost plant 13 [US $ / ton] and discount rate 10 [%]. All these indicators are uniform over time. The strategy of the mining company in this case is to maximize the net present value (NPV) and maximize the reserves. With these values, a critical cut-off grade of 0.585 [%], a marginal cut-off grade of 0.514 [%] and an average grade of 0.850 [%] are calculated.

All experiments were worked with the following geotechnical scenario: height of bench 10 [m], ramp width 30 [m], ramp slope 10 [%], inter-ramp angle 53 ° and minimum phase width 80 [m]. The values were taken for the geometric design of economic envelope and ramp. It is possible to calculate a horizontal distance for the ramp of 100 [m], which will have at each pit level. A priori, geotechnics gives values of: global height of slope with ramp of 210 [m] and two pieces of ramp passing through all the sections of the contour of the pit. Which gives us an overall slope angle of 45 °.

## RESULTS AND DISCUSSION

Applying traditional long-term planning methodology, an optimal final pit is obtained, whose high grades are at the bottom. The envelope contains 22,584 blocks, representing 20 [%] of the original deposit; with 41,119 [kt] of ore and 17,599 [kt] of waste, giving an REM of 0.43 and a total profit of 248 [MUS$]. This pit was denoted as Envelope 1.

From the first preliminary pit design with ramp to Envelope 1, with the mathematical tool, two sectors are obtained in the slope with different number of ramp pieces transiting, allowing the definition of two global angles Mining slope, the first of 42.2 ° between an azimuth of 90 ° to 258 °, and the second of 45.2 ° for the remaining azimuth. Other geometric parameters remain constant, adding an overall height of 220 [m] that has the preliminary design. Applying the traditional long-term planning methodology again, we obtain a new pit, denoted as Envelope 2.

When re-applying the mathematical tool to Envelope 2, a new preliminary design that maximizes the economic benefit (Figure 2) is defined, with an error rate of 0 [%]; in addition to being able to send the greater amount of fine copper to plant. This experiment considered 3 outer and 1 internal frontier layers; as search domain.

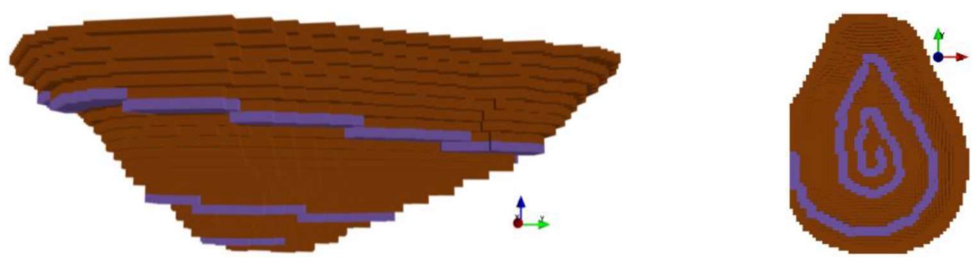

**Figure 2** View in profile (left) and from above (right) of pit design with ramp for Envelope 2

Based on the predesign done with the help of the mathematical model, a final design was generated for Envelope 2. For this a CAD software type was used, which allowed to draw the lines of crest, paw and ramp by bench, leaning on the ramp blocks of the predesign (Figure 3 left). In turn, with the help of CAD software, a design was made to the original envelope, which was not the result of the intervention with the mathematical tool, that is, the Envelope 1, using the art of design. In this opportunity 3 designs were generated, remaining with the one that has greater economic benefit (Figure 3 right).

Then the two geometric design methodologies of ramps were compared. By using the mathematical tool to guide the design, very similar results were obtained to the current state of the art, with an increase of: 1.59 [%] in profit, 1.06 [%] in the tonnage of fine copper shipped to the plant and a 1.40 [%] in total tonnage. However, once the mathematical model finds an optimal solution, only a final design is required which is aided by the mathematical result; versus, the 3 designs with the state of the art, which require more time, since only the experience of the planner is counted.

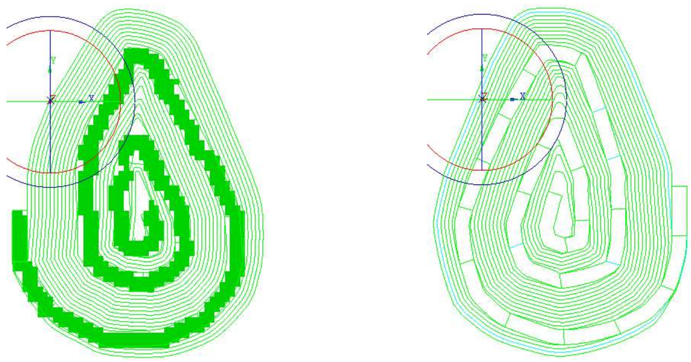

**Figure 3** View from above of pit layer design with ramp for Envelope 2 (left) and Envelope 1 (right)

## CONCLUSIONS

In this paper, we have introduced a mathematical tool that can be used to assist the design of ramps, results were obtained as good as those generated by the current state of art, but in less time. Therefore, when analyzing different scenarios, increased robustness is achieved in the planning process. For this study case, it is possible to find a design that ensures optimum economic, which accelerates, strengthens and simplifies this stage.

This mathematical tool is in the initial stages of its creation. For example, the current version of the model does not allow for switchbacks, and it does not consider connectivity in the case for multiple phases. However, we believe these results to be very promising and expect to address these and other shortcomings in the future, validating the results through the application on multiple case studies.

## ACKNOWLEDGEMENTS

Thanks to CONICYT Basal Grant FB0809: "Advanced Mining Technology Center".

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