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A procedure to generate optimized ramp designs using mathematical programming

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ABSTRACT: Open-pit mine planners have long relied on optimization models for estimating pushbacks without ramps at the block level. Subsequently, they generate an operational design which includes ramps that are required to access the different parts of the mine. This design depends on the time available and the experience of the planner.

In this paper, we present a procedure that (i) uses mathematical optimization to find a modified pushback, which contains the ramp location at the block level, minimizing the impact on the value of the original pushback, and (ii) produces a designed pushback integrating the operational ramp design at the actual pit profile from the modified pushback.

We apply this procedure on several block models and compare to the original pushback, the modified pushback, and the designed pushback. The results show that the designed pushback are consistently close to the original pushback in terms of value and tonnage.

1 INTRODUCTION

Open pit mine planning is a decision-making process that leads to a realistic and actionable plan to profitably extract mineral resources. Planning can be carried out for a wide range of periods from the very short (next shift) to the very long (life of mine) (Whittle, 2011).

The starting point of the mine planning process is a block model in which the ore body is divided into regular blocks; each block with individual attributes, such as, ore grades, recoveries, and tonnages. The block model is economically valued and the profit is assigned to each block (Bley et al., 2010). This block model together with the geotechnical constraints and the long term economic parameters (costs and commodity prices) is the basic inputs for open pit strategic mine planning.

This models allows to compute, for example, the *ultimate pit* (or *final pit*), which is a set of blocks in the block model that contains the total maximum profit while satisfying the operational requirement (Cacetta & Hill, 2003). Within the ultimate pit, the deposit is divided into nested pits: from the smallest pit with the highest value in terms of profit to the largest pit with the lowest profit value (Dagdelen, 2001) for the purpose of establishing a mining sequence. Nested pits are generated by varying the price of the metals being extracted (Hustrulid et al., 2013b).

However, while the ultimate (and nested pits) are widely used for computation of plans, there are no blocks in real mines. Indeed, these computations are used as a guide in later stages to design actual mine. That is, they are only an approximation of the actual volumes of the pit. Indeed, after obtaining the ultimate pit and nested pits, mine designs which represent real profiles (for example with access ramps) are carried out.

On the one hand, the process for computing the ultimate pit and nested pit rely on optimization techniques that guarantee that an optimal solution will be obtained. On the other hand, the open pit operational design stage is carried out using specialized design software, which are tools to aid the user to make designs faster but they do not ensure the profit optimization. Thus, this stage is mostly a manual process in which the optimality depends on the user.

It follows that the quality of the resulting solution depends on the skills, information and time available for the design phase. Even if there exist some criteria to check the quality (for example, measuring the difference in tonnage and value of the optimal pit shell versus the operational pit design), there is no guarantee that the results would be optimal. In addition, the process itself is very slow and time consuming, making it to analyze the robustness of the obtained design.

Unfortunately, ramps are one of the most important aspects of mine planning and they should be included early in the mine planning process since they do have a significant effect on the reserves (Hustrulid et al., 2013a), because they force the addition of waste and/or reducing the amount of ore from the pit shells.

In this paper, we build on previous work to present a methodology that uses a mathematical model and postprocessing in order to generate a pit design which is as close as possible to the results of the optimization process, but complies with actual design considerations. The mathematical model has been already introduced (see Morales et al. 2017 and Nancel-Penard 2019) starts with the optimized pit (at the block level or support) and generates another profile (also at the block support) with enough space for ramps and so that the impact in value is minimized. The postprocessing, which is the emphasis of this paper, then takes this *proto-design* of the phase and generates a design of the pit and ramp.

1.1 *Review of current practices and related literature in mine designs*

At the mine design stage that consists of converting volumes defined at block level into operational ones, it is necessary to smooth the final pit contour and pushbacks. Mine designs must incorporate all the geometrical components of a slope, which include hauling ramps, where trucks can access each of the phases to transport ore and waste to the final destinations.

Generally, ramps' locations are constructed based on the criteria of the mine planner in charge of the operational mine designs of an open pit. One of the issues faced by the mine planner, which is little written about in the mining literature, is gaining initial access to the ore body (Hustrulid et al., 2013a). Some aspects, which the mine planner must consider when realizing operational designs, are:

- Minimum costs on a net present value basis for the transport of ore and waste throughout the life of mine. The preference is to use of long-life haul roads rather than short-life roads as this reduces overall road construction costs and operating costs (Atkinson, 1992).
- Roads exits from the pit wall. This is dependent upon the crusher location and the dump points (Hustrulid et al., 2013a).
- Optimum number of access points to the pit. More access points mean more flexibility but the added cost could be high (Hustrulid et al., 2013a).
- Optimum number of switchbacks. It is desirable to avoid the use of switchbacks in a pit because they tend to slow traffic, cause greater tire wear and various road maintenance problems (Hustrulid et al., 2013a).
- Minimum traffic congestion (Atkinson, 1992).
- Avoidance of areas where slope stability problems could occur (Atkinson, 1992).

Therefore, the planner must deal with many criteria and considerations to generate a design, which means that the current practice does not necessarily maximizes NPV and minimizes operational costs in pit designs.

2 DESCRIPTION OF THE MODEL AND POSTPROCESSING ALGORITHM

In this section we specify the problem to be solved and describe the mathematical model and postprocessing algorithm.

Figure 1 depicts the whole process. As a first stage, we start with a pushback at the block support (for example the ultimate pit or any nested pit). This pit used as an input for an optimization model that looks for a *pre-design pushback* (also at the block support) so that:

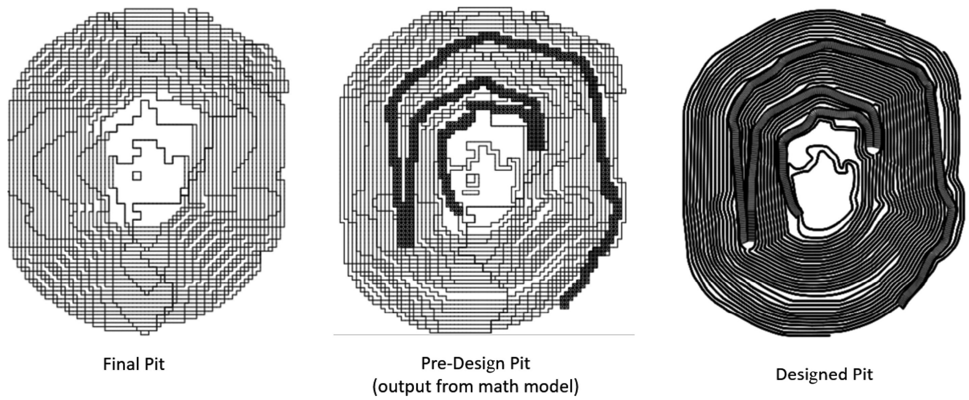


Figure 1. From ultimate pit to designed ramps.

(i) it contains enough space for the ramps, and (ii) it has a value as close as possible to the original pit. Finally, the postprocessing algorithm transforms the output of the algorithm (i.e. the pre-design pushback plus information about the ramp estimated location) and produces an operational pit profile.

2.1 *Computing the pre-designed pushback*

The pre-designed pushback starts with a block model that includes economic values of the blocks and a pit profile. From this, it will select specific points that aim to estimate the block at which the ramp passes at every level (if the ramp is wider than 1 block, it looks at the outer block). These points can be inside or outside the initial profile, with tolerance distances defined by the user. The model uses these points to estimate the blocks that need to be extracted and generate space for a ramp and from that it estimates the total value of the new volume being computed. The goal is then to maximize the value of that goal.

Further details on the equations of the model can be found in (Morales 2017), and an example of the application of this model in (Nancel-Penard 2018), however it is key to mention that as output, the mathematical model generates the following:

– The set of all blocks that should be extracted.
– A set of control points for the ramp, i.e., a list of blocks that form part of the ramp.

It is also important to notice that, since the model works at the block support, everything has to be approximated by blocks. In particular, for example, the width of the ramp, it's slope, etc.

2.2 *Generating the smooth profile*

This step is an algorithm that aims to fit an operational ramp into the pre-design phase obtained from the block model. For this, the algorithm utilizes not only the profile, but the control points of the ramp at each level and aims to interpolate them using an actual ramp.

The algorithm starts uses the block model and the following standard design parameters: berm and haul ramp widths, global slope angle, bench face angle and interramp angle as depicted in Figure 3 (Left), as well as a number of bencher over which to measure the global slope angle. It also takes as input the result of the mathematical model, which is schematically represented in Figure 3 (Right).

Notice that the algorithm does not consider the ramp slope, as this is already taken into account in the optimization model.

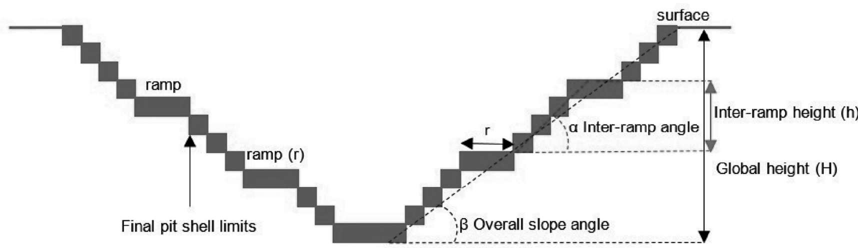


Figure 2. Schematic draw of the pre-design pit at a global scale with the geometrical component of a slope.

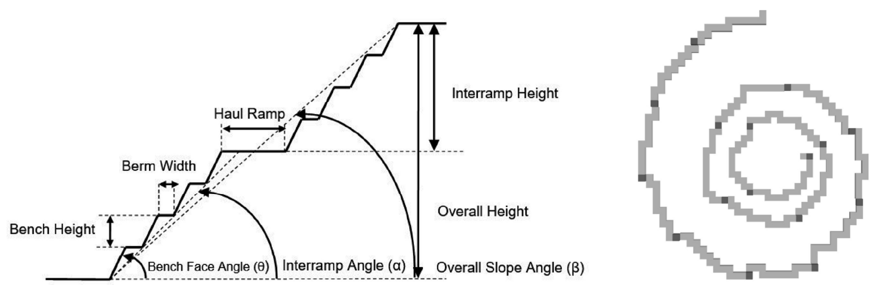


Figure 3. Left: Design parameters for postprocessing algorithm. Right: Output of mathematical model (input for the post processing algorithm). Source: Nancel-Penard et al., In Press.

Table 1. Summary of instances for numerical experiments.

Instance	# total benches	Block size	Global slope angle	Final pit value (MM USD)	Final pit tonnage (MM Ton)
Marvin	30	$15 \times 15 \times 15$	45.6	1,416.2	527.7
Marvin2	30	$15 \times 15 \times 15$	47.4	1,442.3	516.4
KD	18	$20 \times 20 \times 15$	45	647.4	189.9
ZMedium	30	$30 \times 30 \times 15$	45	1,673.7	97.2
ZSmall	14	$15 \times 15 \times 15$	45	1,899.7	541.1

3 NUMERICAL EXPERIMENTS

We consider several block models that are openly available. The models are from the MineLib datasets and provide information not only about block values and coordinates, but also block sizes and precedence arcs.

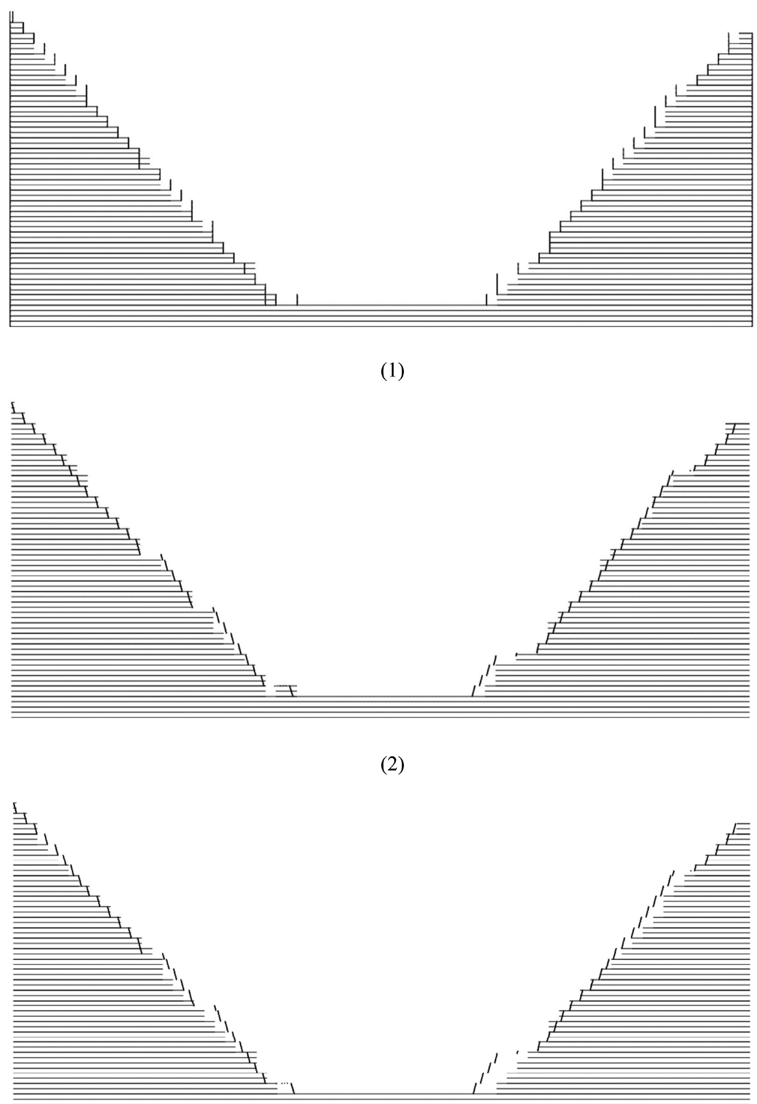
Table 1 summarizes the main aspects of these instances in terms of number of blocks, benches and block sizes, the global and bench face slope angles, and range of variation of the interramp angles used for different experiments and also information about the ultimate pit in terms of the final pit values and tonnage.

4 RESULTS AND ANALYSIS

Table 2 shows the main results of this article for the 5 instances described before. For each instance, we considered a global slope angle and bench face angle, but different values of interramp angles and a number of benches to control the global angle. We report the differences in terms of tonnage and value after the application of the model and algorithm with

Table 2. Performance of the mathematical model and algorithm in terms of tonnage and value differences.

Instance	Global slope angle	Interramp angle range	# Benches to measure global angle	Max pit tonnage difference math model (%)	Max pit value difference math model (%)	Max pit tonnage difference algorithm (%)	Max pit value difference algorithm (%)
Marvin	45.6	50–55	15–20	3%	1%	1%	1%
Marvin2	47.4	50–55	15–20	3%	1%	3%	2%
KD	45	50–55	5–15	14%	10%	15%	14%
ZMedium	45	50–55	10–20	20%	6%	20%	7%
ZSmall	45	50–55	10–15	12%	6%	15%	11%



(1)

(2)

(3)

Figure 4. Comparison of profiles for the Marvin instance. From top to bottom: (1) original pit versus model output, (2) model output vs algorithm output and (3) original pit versus algorthm output.

respect to the values in Table 1, however it is worth noting that most of the differences are due to the gap between the original pushback and the result from mathematical model, with the gap for the algorithm being always less than 2% with regards to the model's result.

As it can be seen from the results, the performance of the total variation in terms of value and tonnage can vary significantly from case to case, however the highest difference is introduced by the mathematical model rather than the postprocessing algorithm, which is even capable to reduce the gap sometimes. This is encouraging, because indeed the large differences are mostly due to the several approximations that the mathematical model must perform in terms to *describe* a ramp in terms of blocks, which do not always fit the bench heigh or ramp width.

Figure 4 depicts the profiles obtained for the *Marvin* instance which can be considered as the *best* case. The figure shows the comparison of profiles between the original final pit and the result of the optimization model, the comparison between the result of the optimization model and the output of the postprocessing algorithm, and the comparison between the original pit and the output of the postprocessing algorithm.

Similarly to Figure 4, Figure 5 represents the same comparison between profiles for the *ZMedium* case, which can be considered the *worst performing* scenario in the results.

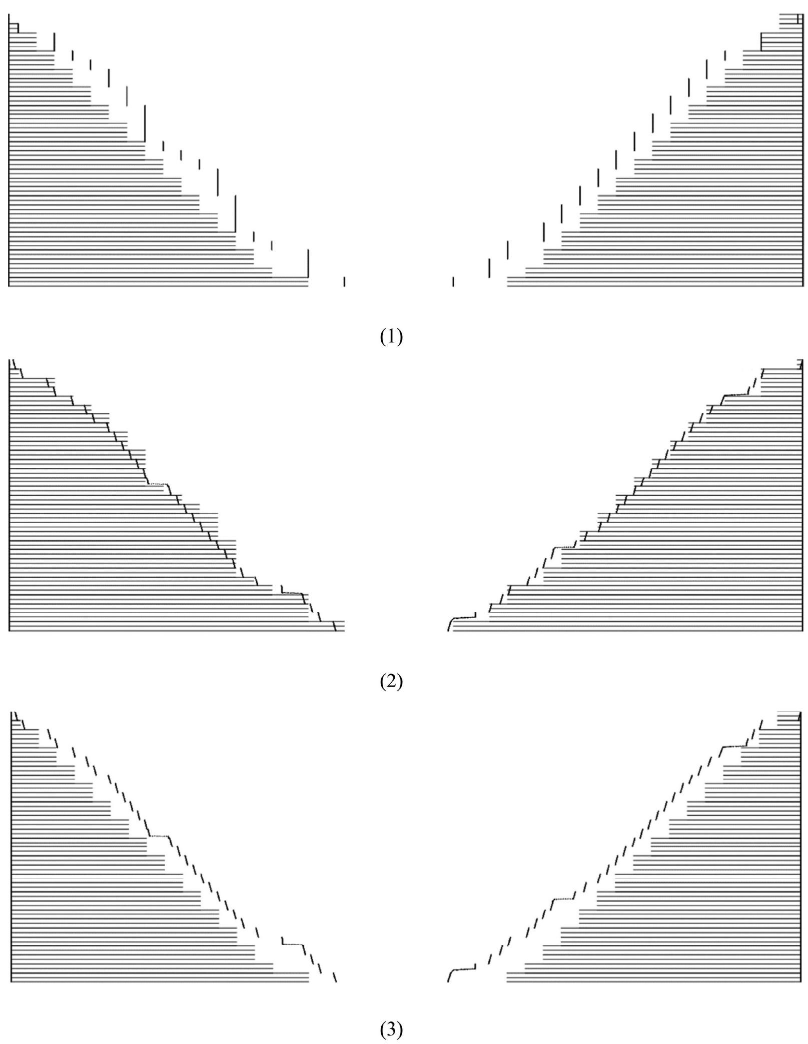


Figure 5. Comparison of profiles for the ZMedium case. From top to bottom: (1) original pit versus model output, (2) model output vs algorithm output and (3) original pit versus algorthm output.

5 CONCLUSIONS

We have presented a methodology that combines an optimization model and a postprocessing algorithm in order to transform an optimized pit profile, computed using block support, into a pit profile that includes an access ramp, and analysed the performance of the methodology over five different block models.

The methodology considers standard design parameters, for which it aims to fit the best ramp so that the total value impact on the initial pit profile is mitigated. Given the operational and design parameters, the methodology is fully automated, therefore providing a valuable tool for constructing the first designs of the mine quickly and therefore allowing to analyse several scenarios with ease.

When evaluated over the different case studies, the methodology shows that it can generate profiles with value and tonnage that are close to the original one, however the differences can be significant, leaving space potential improvement. However, the study also shows that this is mostly due to the difference introduced by the optimization model, which needs to approximate a ramp design using block support. Conversely, the postprocessing algorithm seems very promising in terms of capturing most of the value of the initial solution, even improving it sometimes.

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