Blast Pattern Expansion: A Heuristic Approach

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Abstract

Rock blasting, in particularly the drilling process, is one of the first processes in the stage of rock fragmentation and plays a fundamental role by influencing all the following stages. Given its importance, some proposals to optimize this process have been presented over the last few years. These proposals, while having different approaches, aim (in a large part) to minimize the costs of drilling and blasting respecting the limits of fragmentation required by primary crushing. Reviewing some recent articles leads us to an enriching experience, since the authors of these articles clearly model the problem, but do not address the mathematical solution of these models, which in turn, given their non-linear nature, have no directly and easy solution. Simple and even robust optimizers present in the market show different results and often do not converge to a single solution. To address this problem, an adapted gradient heuristic-based model was developed to try to find optimum values. Heuristics search for values of stemming, subdrilling, burden and spacing that minimize the costs of blasting and drilling. This search, which by the nature of the heuristic moves the solution in the direction of the gradient with maximum decrease to find optimal solution, found values that in turn, when compared with values presented by market solutions not only equaled them as, in some situations, even improved the proposed solution. The algorithm was tested and validated on the field, and although the results have already been presented in papers published in the last year by the authors of this paper, it is now presented with its mathematical formulation and comparison with the other solutions. This approach is expected to be able to improve (and even demystify) the process of pattern expansion and be the basis for future work in the continuation of the optimization process.

Introduction

Numerous studies and independent models of Mine to Mill were developed recently and have shown the potential for significant downstream productivity improvements from blast fragmentation (Chadwick, 2016). It’s easy to understand this "fever" by optimization since (this is one of various reasons) the productivity increases 10-20% and the operating costs are low (McKee, 2013) . The first important part in this optimization process is the blasting since it directly influences over the production efficiency and energy consumption of shovel, loading, transportation, crushing and milling (Li, Xu, Zhang, & Guo, 2018). Optimize the blast process respecting the necessary fragmentation levels for next steps it’s not an easy task but was mentioned in various papers and the pedagogic “Blast Pattern Expansion” (Miranda, Leite, & Frank, 2017) paper is a good example of it. However, this papers usually don’t present the formal way to fix the models and for this reason was developed and proved by this research a heuristic based on gradient descent methods. The authors of this articles will explain the necessary steps to find values of burden, spacing, subdriling and stemming that minimize the total cost of drilling and blasting but preserve the level of fragmentation. The comparison between these heuristic and other solvers on the market showed the benefits and potential of this technique.

Background

Blast

The blast operation has a big impact in the all aspects of a mining process. It affects all the other associated sub-systems, i.e. loading, transport, crushing and milling operations (Tamir & Everett, 2018). In order to achieve the desired blast results framed to the operation (such as desired fragmentation), it’s important to take into account some aspects such as rock proprieties, type of explosive, blast design parameters and geometry, etc (Bhandari, 1997).

Many authors developed a series of empirical formulas that associate relations between diameter, bench high, hole length, stemming, charge length, rock density, rock resistance, rock constants, rock seismic velocity, explosive density, detonation pressure, burden/spacing ratio and explosive energy, in order to have the best pattern design to different conditions (López Jimeno, López Jimeno, & Garcia Bermudes, 2017). Some parameters such as ground conditions, results, operation details and geology will be decisive to the blast design.

Fragmentation

One of the main objectives in blasting is to generate rock fragments at a certain range of sizes (Cunningham, 2005). This step will influence the next steps, such as loading, transport and crushing and the main objective is to have an effective result (particle size, shape, etc.) that fits in the mine/quarry needs (Brunton, Thornton, Hodson, & Sprott, 2003). The necessity to predict this fragmentation is important and many equations where developed all around the world with the same objective.

One of the prediction models it’s the Kuz-Ram model and is based in three main equations:

Kuznetsov Equation (equation 1), presented by Kuznetsov, determines the blast fragments mean particle size based on explosives quantities, blasted volumes, explosive strength and a Rock Factor.

$$x_m = AK^{-0,8}Q^{1/6}\left(\frac{115}{RWS_{ANFO}}\right)^{19/30}$$ **Equation 1**

Where X_m= Medium size of fragments (cm); A= Rock factor; K = Powder factor (kg/m3); Q= Explosive per hole (kg); 115 = Relative Weight Strength (RWS) of TNT compared to ANFO; RWS_{ANFO}= Relative Weight Strength (RWS) of the used explosive compared to ANFO.

Rosin-Ramler Equation (equation 2), represents the size distributions of fragmented rock. It is precise on representing particles between 10 and 1000mm (0,39 to 39 in) (Catasús, 2004, p. 80).

$$P(x) = 1 - e^{-0{,}693\left(\frac{X}{X_m}\right)^n} \qquad \textbf{Equation 2}$$

Where P= Mass fraction passed on a screen opening x, n = Uniformity Index

Uniformity index equation determines a constant representing the uniformity of blasted fragments based on the design parameters indicated in equation 3.

$$n = \left(2{,}2 - \frac{14B}{d}\right) \times \sqrt{\frac{1+\frac{S}{B}}{2}} \times \left(1 - \frac{W}{B}\right) \times \left(\left|\frac{h_f - h_c}{L}\right| + 0{,}1\right)^{0{,}1} \times \frac{L}{H} \qquad \textbf{Equation 3}$$

Where B = Burden (m), S= Spacing (m), d = Drill diameter (mm), W = Standard deviation of drilling precision (m), h_f = Bottom charge length (m), h_c = Column charge length (m), L = Charge Length (m), H = Bench height (m).

Heuristic

A heuristic is a procedure that tries to discover a possible good solution, but not necessary the optimum one (Hillier & Lieberman, pág. 563) and have as objective (Polya, 1957) the study of the methods and rules of discovery and invention. Although the limitation to avoid local optimums (Metaheurísticas, 2007, pág. 3) this kind of technique is very useful for unimodal problems. We can define a problem as unimodal if only exists one maximum (or minimum) for a known domain (Cuevas Jiménez, Oliva Navarro, Osuna Enciso, & Díaz Cortés, 2017) has showed below:

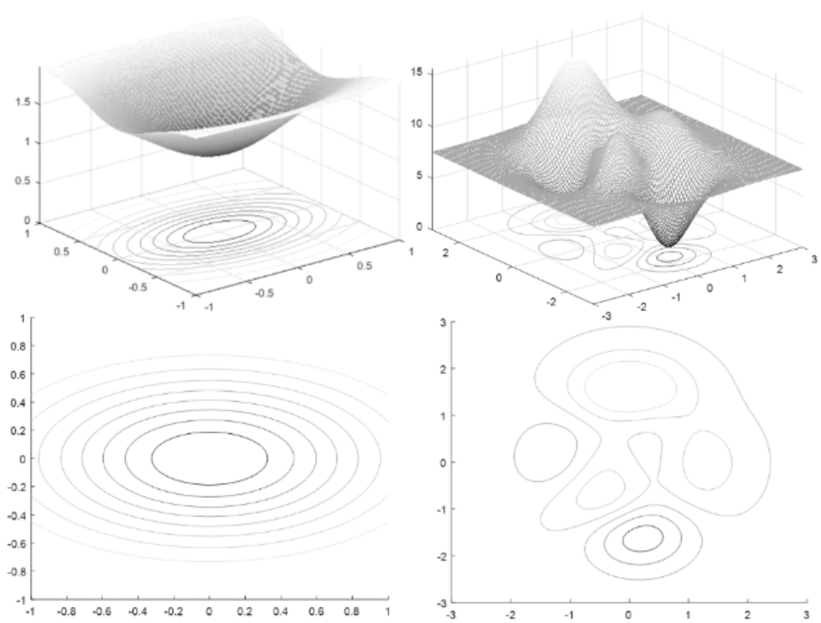

Figure 1. Difference between unimodal (left) and multimodal problems (right).

Gradient Descent

This classic method, also called Gradient Method, is one of the first used for multidimensional objective functions and it is an important base for another modern techniques of optimization (Golub & Öliger *in* Cuevas *et al*). This method is based in a start point that is a feasible solution. Then, the result is moved in the direction of the gradient until the exit criteria is reached. The generic function is represented as bellow (equation 4):

$$\boldsymbol{X_{k+1} = X_k - \alpha \cdot g\big(f(X)\big)} \qquad \textbf{Equation 4}$$

Where, k = actual interaction, α = the size of the step and $g\big(f(X)\big)$ = the gradient of the function "f" at the point "X";

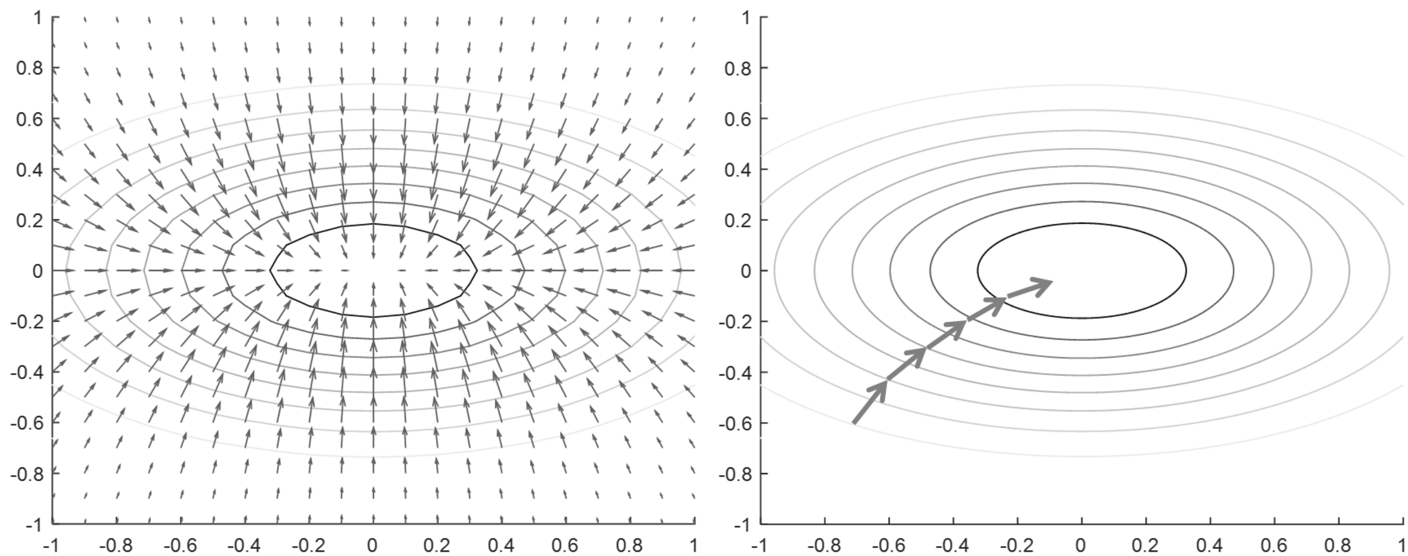

Figure 2. Vector field and movement of the gradient descent algorithm.

More details can be founded in Bronson, p. 14, Campos, Oliveira, & Cruz, p. 314 or in Mathews & Fink, p. 447.

Model

The objective of a mathematical model is to represent mathematically an abstract problem found on the nature. A mathematical problem, to be interpreted and solved, needs to involve three elements (Tormos & Lova, 2003):

- Decision variables;
- Restrictions or decision parameters;
- Objective functions.

For this model, some information must be introduced by the starter parameters (respecting the international unit system):

Bench high, diameter of the borehole, percentage of material under the crusher gape limit, crusher gape limit, rock factor, explosive data (density and RWS), required total volume and costs: cost per kilo of explosive, cost per hole of initiation system and cost per drilled meter.

This model was explained by the authors of this paper previously (Miranda, Leite, & Frank, 2017) and the pedagogic resume is presented:

$$\boldsymbol{Decision\ Variables}: \boldsymbol{Burden, spacing, stemming, subdrilling}$$

$$\mathbf{min}\, \boldsymbol{Z} = \boldsymbol{bulk\ total\ cost} + \boldsymbol{initiation\ system\ total\ cost} + \boldsymbol{driller\ total\ cost}$$

Restricted to:

$$\boldsymbol{lower\ limit} \leq \frac{\boldsymbol{Spacing}}{\boldsymbol{Burden}} \leq \boldsymbol{upper\ limit}\ ^{\mathbf{1}}$$

$$\boldsymbol{lower\ limit} \leq \frac{\boldsymbol{Subdrilling}}{\boldsymbol{Burden}} \leq \boldsymbol{upper\ limit}\ ^{\mathbf{1}}$$

$$\boldsymbol{lower\ limit} \leq \frac{\boldsymbol{Stemming}}{\boldsymbol{Burden}} \leq \boldsymbol{upper\ limit}\ ^{\mathbf{1}}$$

$$\boldsymbol{Production} \geq \boldsymbol{volum\ required}\ ^{\mathbf{2}}$$

$$\boldsymbol{X}_{(\%)} \leq \boldsymbol{Crusher\ gape\ limit}\ ^{\mathbf{3}}$$

$$\textbf{Burden, spacing, subdrilling, stemming} \geq \mathbf{0}$$

Where 1 are Ash’s design standards restrictions, 2 the production restrictions and 3 the fragmentation restriction.

Due to the nature (nonlinear) of the necessaries equations to predict fragmentation and the relation between the decision variables, a classic method to solve linear problems as simplex (Dantzig, 1963) can’t be used.

To understand the nature of the problem was evaluated all possible solutions for the range:

- $\mathbf{2} \leq \boldsymbol{Burden} \leq \mathbf{4}$
- $\mathbf{1} \leq \frac{\boldsymbol{Spacing}}{\boldsymbol{Burden}} \leq \mathbf{2}$
- $\mathbf{0.3} \leq \frac{\boldsymbol{Subdrilling}}{\boldsymbol{Burden}} \leq \mathbf{0.5}$
- $\mathbf{0.7} \leq \frac{\boldsymbol{Stemming}}{\boldsymbol{Burden}} \leq \mathbf{1}$

Was evaluated all possible solutions with a variation step of 0.1 for each variable. In each step the solution (total cost) was evaluated. The general format, for a specific relationship subdrilling by burden and stemming by burden is showed in Figure 3.

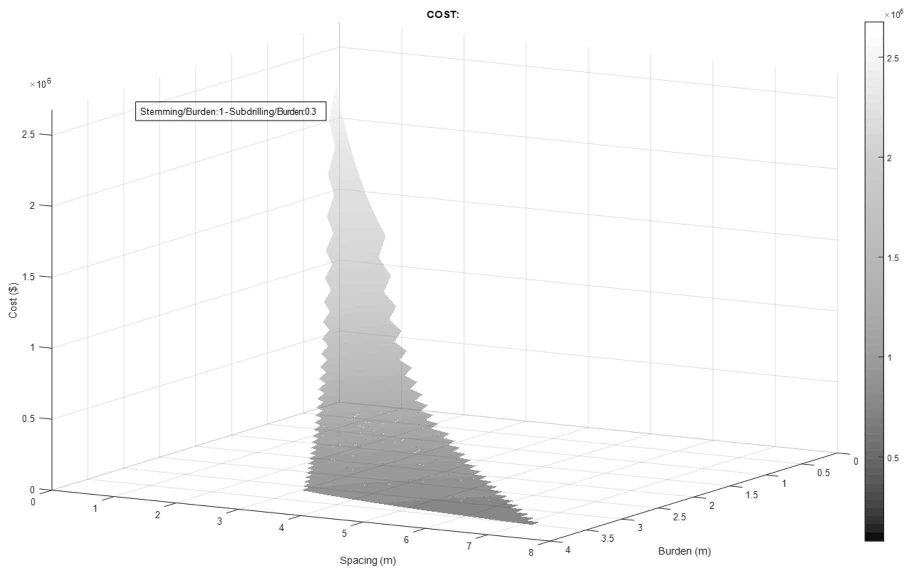

Figure 3. Total cost fixed relation between stemming by burden and subdrilling by burden.

For highest values of burden and spacing the total cost decreases (as expected). It was necessary to use the fragmentation as a limit - Figure 4

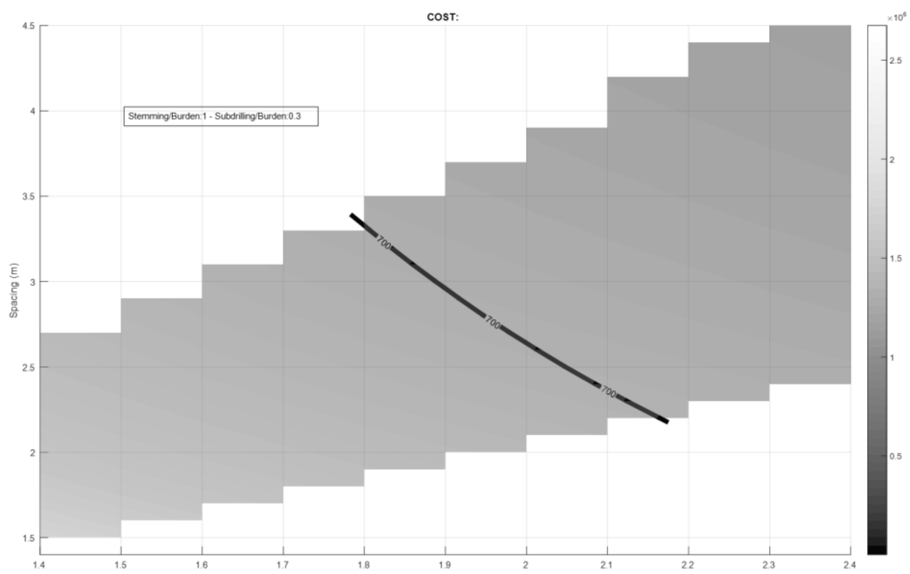

Figure 4. Limit of fragmentation

To identify the behavior of the fragmentation curve limit when the relation between subdrilling by burden and stemming by burden changes the graph of Figure 5 was generated.

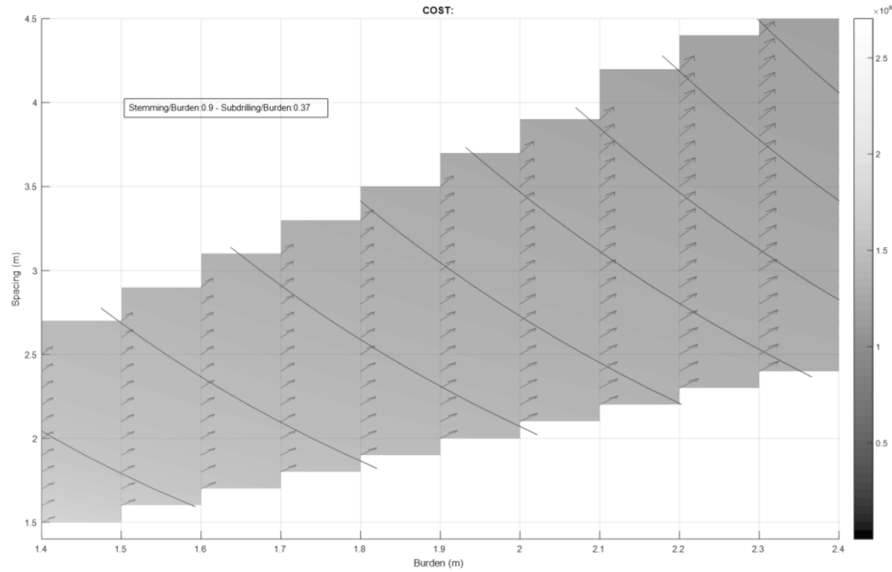

Figure 5. Behavior of the limit fragmentation curve for different values of subdrilling by burden and stemming by burden.

Was possible to observe that when the stemming by burden decreases and the subdrilling by burden increases the curve moves to the right and the total cost decreases. Based on it, the first step was to use stemming by burden as minimum as possible and subdrilling by burden as maximum as possible.

The next step was to evaluate the cost curve and find the interception between it and the limit fragmentation curve - Figure 6. The behavior of that point indicates that is possible to use a unimodal treatment for the problem.

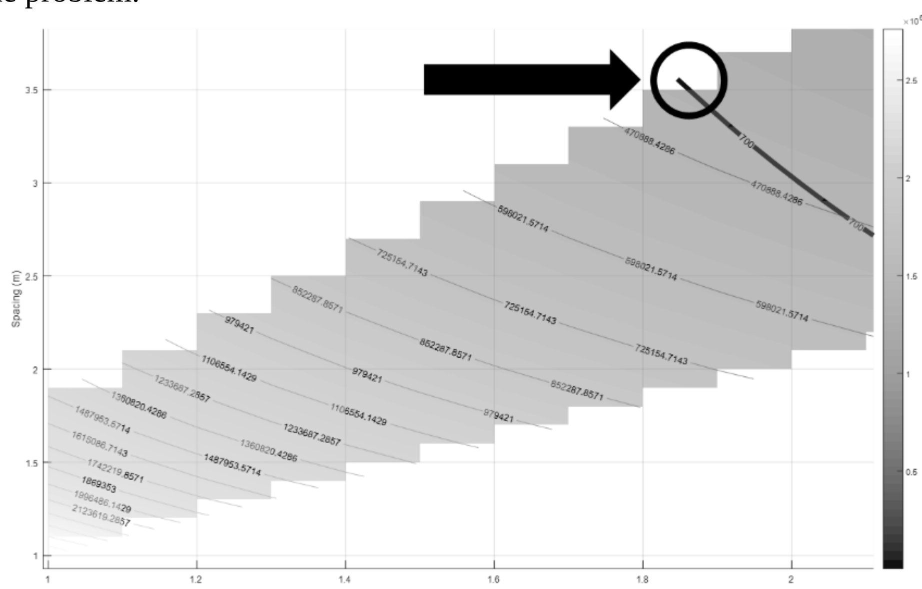

Figure 6. The interception between cost and fragmentation limit (minimum cost).

The algorithm must be good enough to find the interception between the cost curve and the fragmentation limit curve. The generic flow representing the algorithm based on gradient descent is showed in Figure 7.

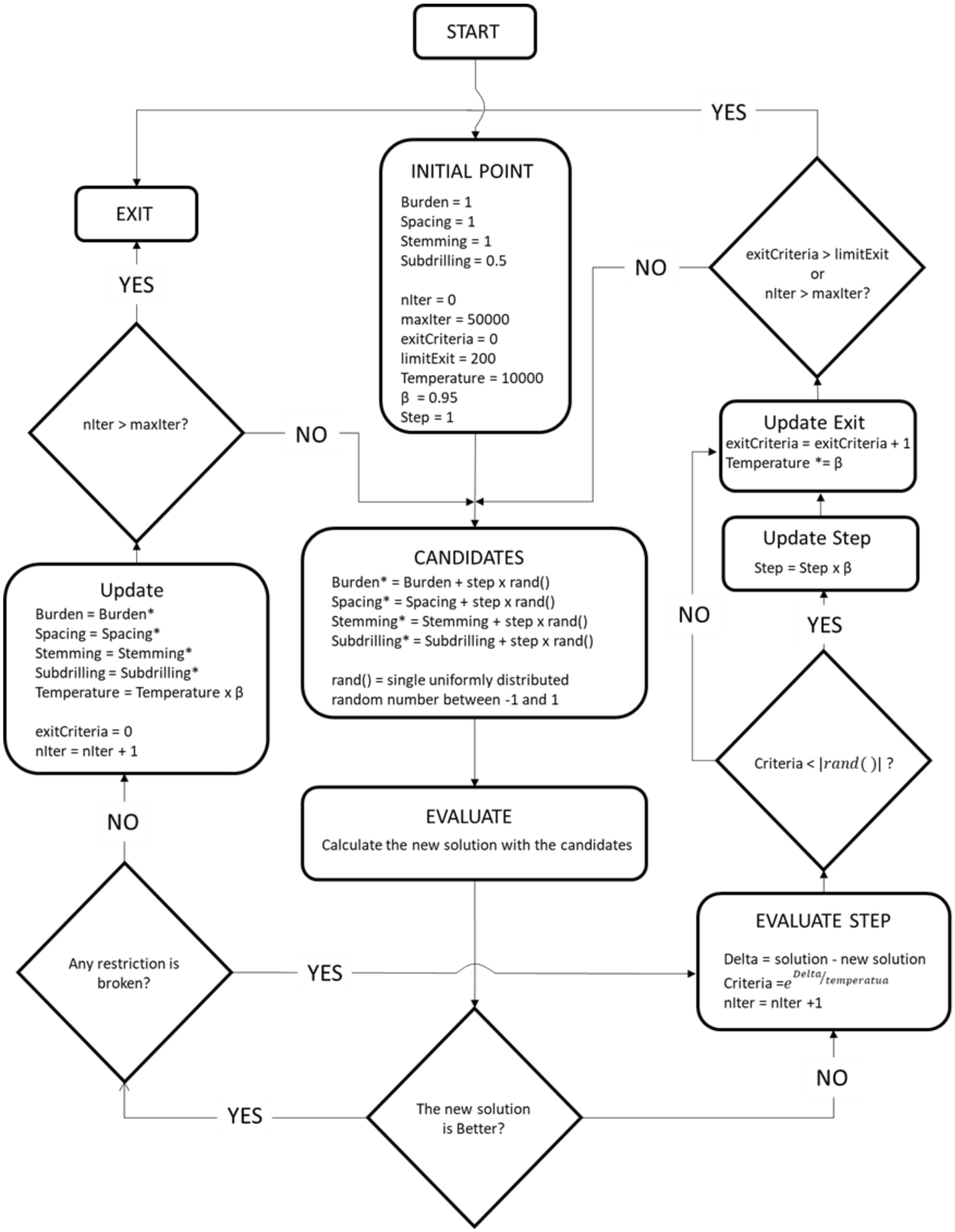

Figure 7. Adapted gradient heuristic

The algorithm increases burden and spacing values freely until to find the boundary of fragmentation limit curve - Figure 8. In the moment it gets values near the fragmentation limits the algorithm will move the solution in a parallel way to the curve, increasing the spacing and decreasing the burden (gradient direction) until find a value that can’t be improved, just like below:

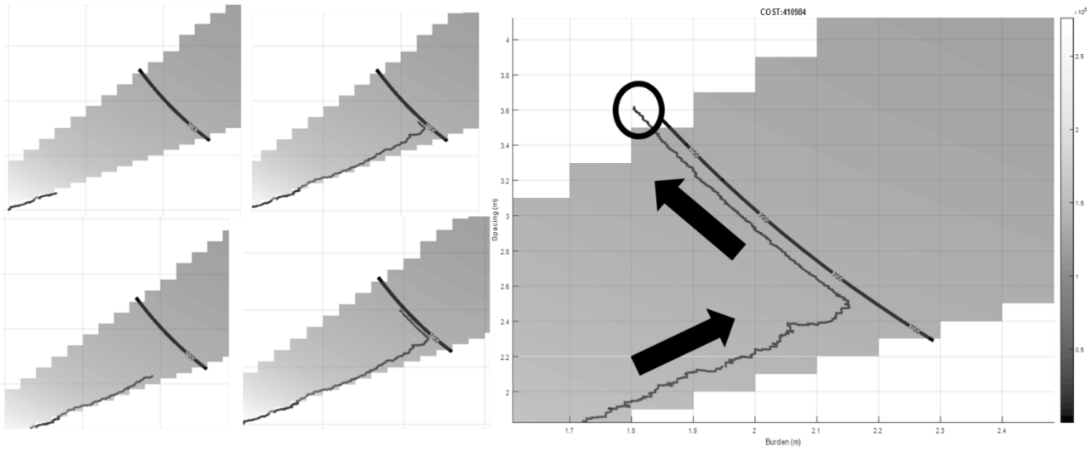

Figure 8. Detailed movement of the algorithm

Field Application

The field application procedure was presented by Miranda, Leite, & Frank, 2017 at EFEE 2017 and there are presented the initial parameters used by the operation and the ones determined by the procedure mentione before. It was defined step by step process to increase the pattern and avoid abrupt changes on the field and this process is presented on the Table 1.

Table 1. Pattern expansion process

	Initial Stage	*Stage 1*	*Stage 2*	*Stage 3*	*Stage 4*	*Stage 5*	*Stage 6*	*Stage 7*	*Stage 8*	*Stage 9*
Diameter (mm)	140,0 mm	140,0 mm	140,0 mm	140,0 mm	140,0 mm	140,0 mm	140,0 mm	140,0 mm	140,0 mm	140,0 mm
Bench High (m)	10,0 m	10,0 m	10,0 m	10,0 m	10,0 m	10,0 m	10,0 m	10,0 m	10,0 m	10,0 m
Burden (m)	3,9 m	**4,0 m**	4,0 m	4,0 m	4,0 m	4,0 m	4,0 m	4,0 m	4,0 m	4,0 m
Spacing (m)	4,7 m	**4,8 m**	**4,9 m**	**5,0 m**	**5,1 m**	**5,2 m**	**5,3 m**	**5,4 m**	**5,5 m**	**5,6 m**
Subdrilling (m)	1,2 m	1,2 m	1,2 m	1,2 m	1,2 m	1,2 m	1,2 m	1,2 m	1,2 m	1,2 m
Stemming (m)	3,2 m	**3,3 m**	**3,4 m**	3,4 m	3,4 m	3,4 m	3,4 m	3,4 m	3,4 m	3,4 m

Discussion

In term of production results and field actions the authors incremented 10 cm (3,9 in) on burden and spacing on each stage. The study stagnates on the stage 4 (due to external reasons that are mentioned on the paper presented by Miranda, Leite, & Frank, 2017) and the potential saving were calculated. The blasted volume with the Stage 4 geometry was 5 020 000,00 m^3 (6 565 912.11 y^3) and the estimated holes reduction was 2779 holes which represents savings of 826 019,59€ (aprox. 940 233,00 USD) for drilling, explosives and accessories.

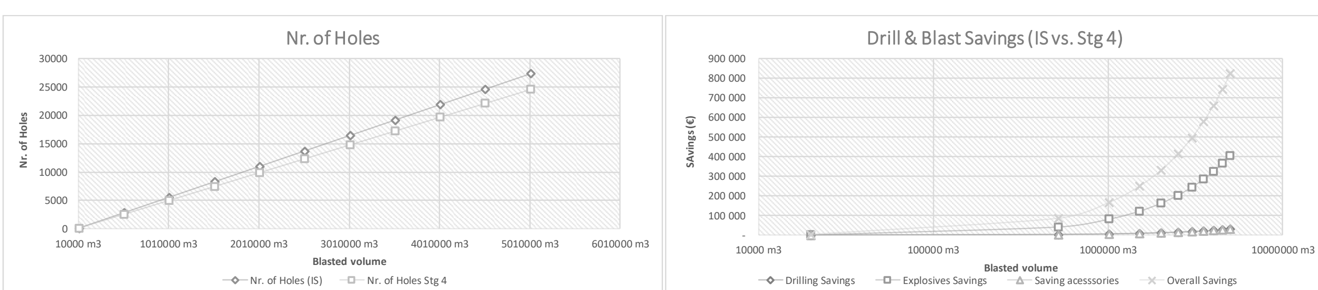

Figure 9. Holes reduction and Drill&Blast total savings

Once again, the use of this kind of numerical approaches proved to be very useful on blast pattern design and optimization. Is a field that has much more ways to go, in specific, load and haul techniques, primary crusher and mill optimization. The authors encourage the reader to shift the mind set of blast optimization to mine optimization and not only thinking and caring on the product generate by blast but picking the "*big picture*" of the full mine chain and reinforce it – more studies will be presented soon.

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