Blast Pattern Expansion
A numerical Approach

V. Miranda, F. Leite & G. Frank
O-Pitblast Lda., Porto, Portugal

ABSTRACT: This document investigates a newly developed mathematical model with the objective of cost optimization on the overall blasting process. This model is based on blast pattern expansion with automatic adjustment of the burden, spacing, stemming, sub-drilling and number of holes in order to guarantee the production demands in terms of blasted volume. Hole geometry, bench-high, rock factor and explosive information are used as inputs. The main idea is to apply numerical methods to find a minimum local that improves the cost when compared with the traditional/empirical techniques. Newton-Raphson and several Gradients Methodologies were used to build an algorithm to reach the desired results. This technique was implemented inside a blast design and optimization platform, used on the validation of this technique. Real fragmentation data was collected by photo analysis and the field work was coordinated by O-Pitblast, Lda. – Technical Department Team. For the model validation, the authors calculated the cost of previous blasts and collected fragmentation information. After that, an optimized blast was planned (where the fragmentation levels were maintained) and the final cost was estimated. The results of this technique demonstrate the cost reduction on a blast while the fragmentation was guaranteed. This kind of approach on blasting optimization procedures showed to be very useful and easy to apply.

1. INTRODUCTION

In the mining world, rock blasting is one of the main procedures of ore winning process (Hustrulid, 1999). The use of explosives, to break and fragment rock, is the fastest and efficient procedure to make it transportable has become a world-wide used technique. The majority of mines and many civil works recurs to the use of explosives and, since 1627 (the first time explosives were used for rock blasting), lots of blasting techniques were developed (Konya & Walter, 1990).
On one hand, these techniques were established in order to optimize the use of explosive energy and in the other hand, more recently, reduce the overall cost of the operation maintaining blast results' quality.

Nowadays, with the cost optimization pressure in the majority of mining companies, is compulsory to analyse each mine-to-mill operation and get the best results from it. This document is about a new drill and blast technique for blast pattern expansion in order to reduce the price but keeping always the demands from load, haul and treatment plant.

2. BACKGROUND

2.1 Rock blasting

The three main factors affecting the blast results, depends on explosive selection (and its quality), blast design and the procedures implemented to replicate this design. It's important to understand the rock characteristics, structures and behaviour when submitted to a certain kind of stress generated by explosives (Bhandari, 1997).

Empirical research and evidences on blasting operations helped to develop a series of blast design formulae in order to propose guidelines for the design process. Is believed, that these important "rules" are meant to be applied with the objective to achieve the desired blast results in an initial stage of any operation (Jimeno, Jimeno, & Carcedo, 1995; p. 200). The results, ground conditions, operation details and geology will be the real decisive kpi's to define the blast design.

As mentioned by Jimeno, Jimeno, & Carcedo, 1995, there are a series of authors, mining engineers and researchers that developed empirical formulas, for pattern design, involving 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;
- Explosive energy.

Some of the researchers are Andersen (1952), Pearse (1955), Hino (1959), Allsman (1960), Ash (1963), Langefors (1963), Hansen (1967), Konya (1972) and Lopez Jimeno, E(1980). In Figure 1 are presented some of these parameters on a bench blasting model.

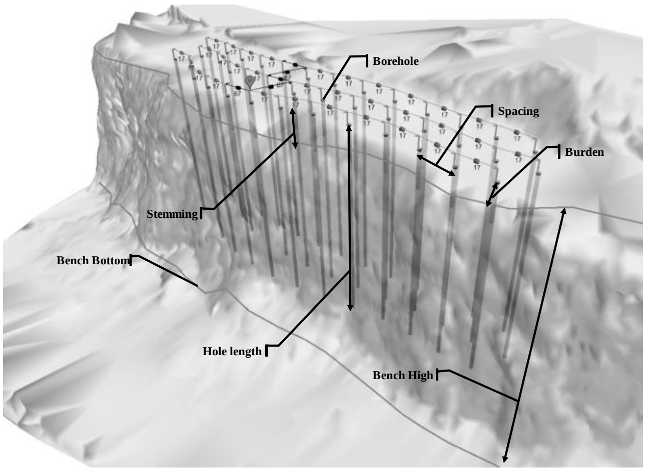

Figure 1. Bench blasting overview.

2.2 Fragmentation

Humans always tried to understand the future. The same happens with mining engineer trying to predict their blast results. In this case, for fragmentation results and prediction, a world-wide well-known model is presented by Cunningham, 2005– Kuz-Ram Fragmentation model.

Despite several models were developed along the years, the simplicity offered by Kuz-Ram model makes it one of the most used prediction models (Cunningham, 2005). This Model 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.

$$x_m = AK^{-0,8}Q^{1/6}\left(\frac{115}{RWS_{ANFO}}\right)^{19/20} \quad (1)$$

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 (Catasús, 2004; p80).

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

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.

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

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).

2.3 Optimization models

The majority of problems or daily decisions can be interpreted as a mathematic model composed by a set of functions. This conjunct of functions when correlated can generate a range of solutions that will be limited by decision variables and restrictions. This way, is necessary to define an objective function to define the problem (Hillier & Lieberman, 2005).

For the present study, since is pretended open the blast pattern to minimize the cost keeping a certain degree of fragmentation, the objective function is the minimization of blast total price by maximizing the *burden* × *spacing* relation. Considering that this kind of problem has non-linear variables - variables inter-dependents between each other's (Wagner, 1975) - was used a non-linear optimization method.

This type of mathematical problems can be complex in the terms that in optimizing field involving non-linear variables, there are several solutions for the problem. The reason settles on the existence of multiple and global minimums/maximums on the functions associated to these kinds of resolutions.

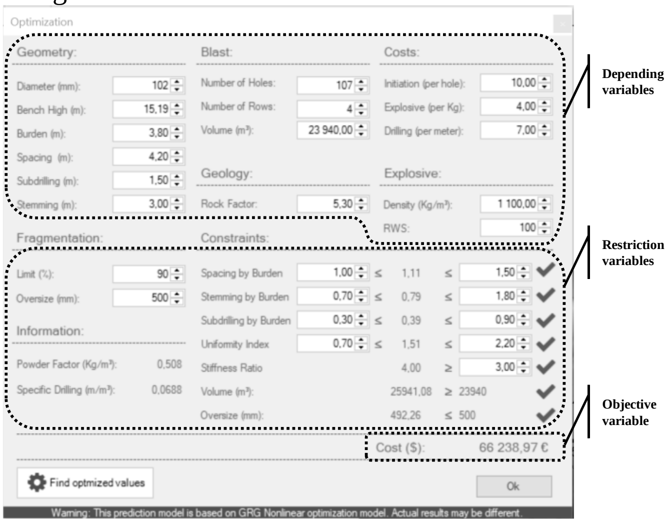

Figure 2. Blast design optimization non-linear variables

3. PATTERN EXPANSION PROCESS

A pattern expansion process demands several steps in order to determine the best blast parameters (to be changed) and avoid production and safety issues.

3.1 Geology gathering

Naturally, mining and explosives engineers need to understand what they are blasting. The first step of a blast process is to try to understand the rock that is meant to be blasted. Identify the exact parameter, in terms of geology and rock structures, that affect the blast and determine the easiness of a rock to break when submitted to an explosive stress, was always a complex process. The practice field experience still plays the major role when the discussion is about the future blast results (Persson, Holmberg, & Lee, 1993). In the next chapters the authors will present a new methodology to, statistically identify this rock factor or rock influence in the process of fragmentation prediction.

3.2 Pattern planning

The second step on blast planning is the definition of its volume and general dimensions. This should be limited by operation characteristics like blasted volume needed, drilling and explosive supplier capacity Load&Haul availability and production. The general planning department generates a blast polygon with certain characteristics. Holes are distributed inside the polygon in order to provide the best energy or powder factor (kg of explosives per m^3/t of rock) distribution. The sequence of diagrams of Figure 3 shows the overall process.

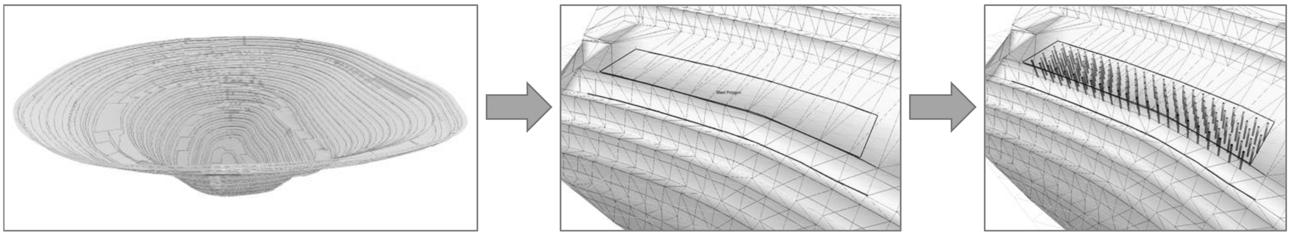

Figure 3. Blast design process

3.3 Fragmentation prediction

As mentioned before, based on primordial geology analysis and blast pattern characteristic it's possible to infer (with a determinate degree of confidence) the size distribution of blast fragments (Figure 4). This first approach allows engineers to assess if their blast will achieve operation needs. Since it depends on a rock factor or rock constant, and the knowing that the crust can be very heterogenic, the prediction model needs to be constantly calibrated in order to provide reliable results. It will be explained afterwards.

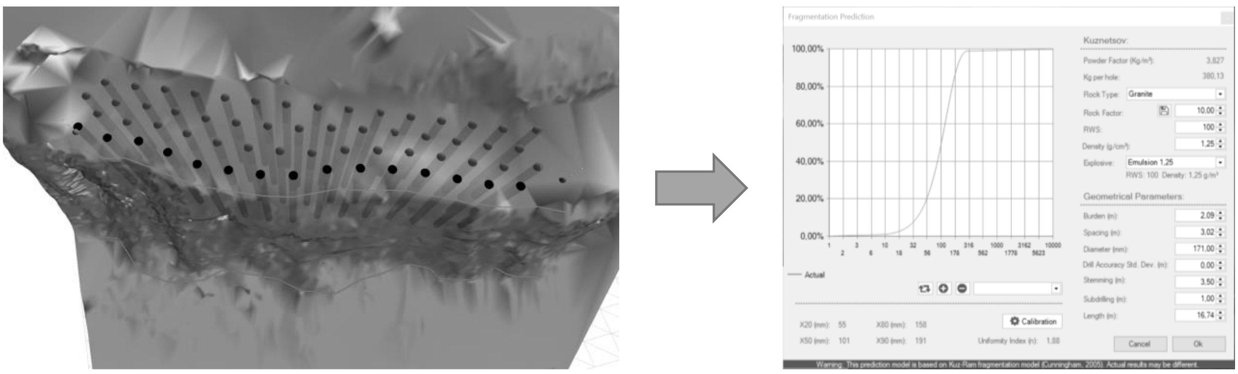

Figure 4. Fragmentation prediction

3.4 Fragmentation Analysis

The way authors found to calibrate the fragmentation curve was by comparing the predicted fragmentation with the actual one. The last one can be obtained by photo analysis. There are several tools in the market that provide the needed technology to estimate the block size in a muckpile. In this research was used the iPad and iPhone WipWare's application, which turned to be a very useful and accurate tool.

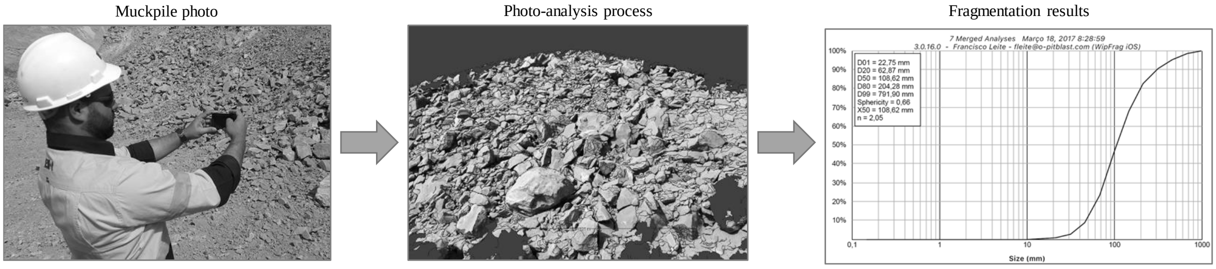

Figure 5. Fragmentation Analysis (WipWare®)

3.5 Model Calibration

Based on the described linear optimization method, the process to calibrate the rock factor/rock influence constant, analyses the predicted and measured X20, X50, X80 and X90 to obtain a perfect match between the two fragmentation curves (Figure 6).

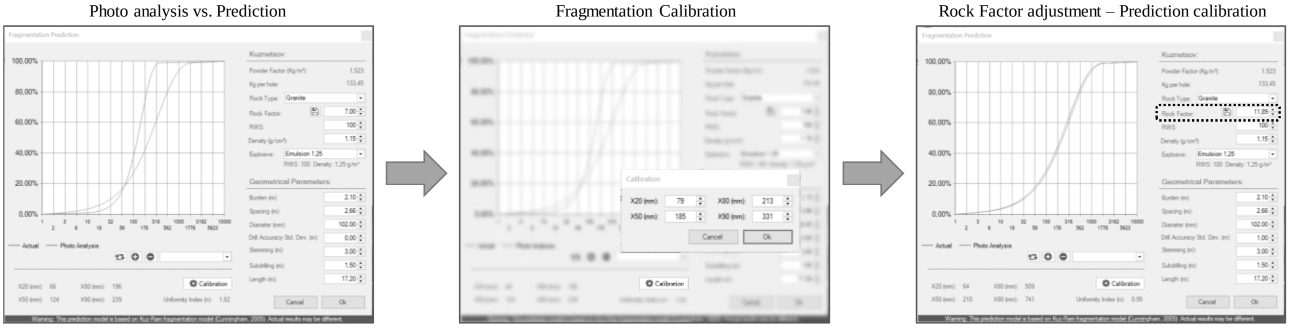

Figure 6. Rock factor calibration process

3.6 Results demands and application

On the changes application stage, there is the need to define the fragmentation restrictions. The model will find the best design parameter (optimum global points), such as burden, spacing, stemming, subdrilling, taking into account the restriction defined, to reduce the blast cost (objective function) – see Figure 7 – and this last one based on the fragmentation restrictions calculated by the Kuz-Ram model. The design parameters restrictions, are based on empirical ranges that can be inspired by the investigation results of the researchers mentioned on the background chapter.

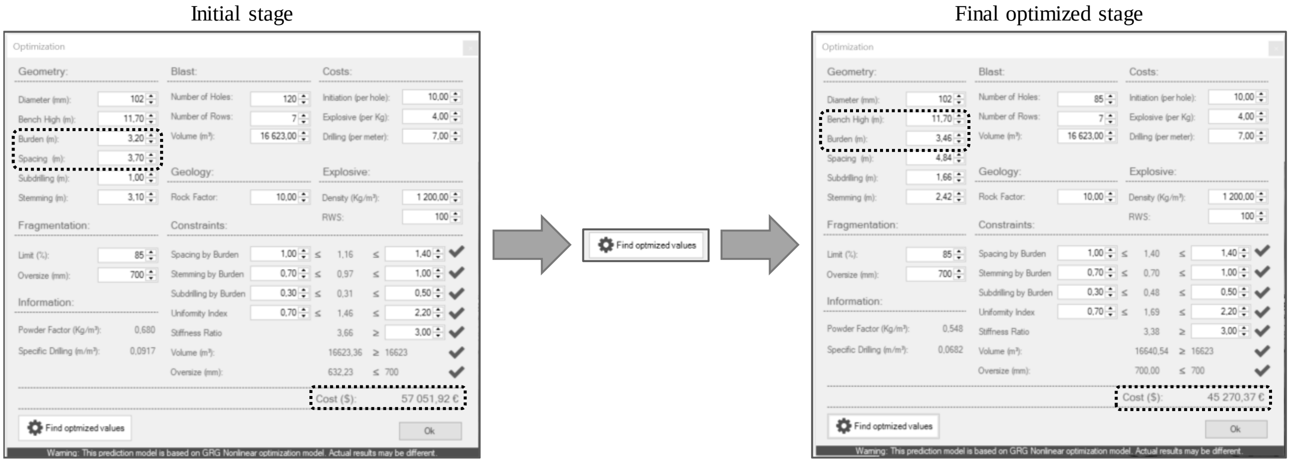

Figure 7. Optimized design parameters (optimum global points)

4. CASE STUDY AND RESULTS ANALYSIS

The next points detail each step of the optimization process (based on the methodology described before) and presents some of the achieved results.

4.2 Initial stage (IS)

The original situation’s benchmarking is a very important point to record. Every field change must be gradual and studied individually to identify potential issues or deep improvements on the process.

The initial stage of the blast designs and results were recorded.

4.2.1 IS Design and Results

In terms of design, the analysed operation blast presented the parameters shown on Table 1 and fragmentation results on Table 2.

Table 1. IS Blast design parameters

Parameter	Value
Burden	3,9 m
Spacing	4,7 m
Diameter	140,0 mm
Stemming	3,2 mm
Subdrilling	1,2
Bench High	10
Powder Factor	0,84 kg/m3

Table 2. IS Fragmentation results

Size	Kuz-Ram Prediction	Photo Analysis
X20	99 mm	42,57 mm
X50	212 mm	149,32 mm
X80	373 mm	302,67 mm
X90	475 mm	587,39 mm
UI	1,49	0,99 mm

4.3 Rock factor calibration

Rock factor (rock blastability influence) parameters are present in the Table 3. These values were used to predict further designs and pattern expansion plans.

Table 3. Rock factor calibration

	Prediction	Best fit
Rock Factor	7,5	5,29

It is possible to observe that the obtained fragmentation from photo analysis is slightly smaller than the prediction. Since Kuz-Ram models retrieve higher values of fragmentation when rock factor is higher (meaning the higher the rock factor the hardest is to break that rock) is understandable that the best fit factor must be smaller.

4.4 Application

With the calibrated rock factor, applied on the described on the non-lineal optimization model process, the design parameters, that best fulfils the empirical restrictions and match the fragmentation demands (X90 ≤ 400,00mm), were determined (Table **4**.)

Table 4. Non-Linear optimization model optimization

	Initial Parameters	**Non-Linear Optimization Model**
Diameter	140,0 mm	140,0 mm
Bench High	10,0 m	10,0 m
Burden	3,9 m	**3,99 m**
Spacing	4,7 m	**5,58 m**
Subdrilling	1,2 m	1,2 m
Stemming	3,2 m	**3,39 m**
Number of Holes	120	**99**
Volume	21996,0 m3	21996,0 m3
Initiation Systems (per hole)	€ 11,00	€ 11,00
Explosive (per kg)	€ 0,95	€ 0,95
Drilling (per meter)	€ 12,50	€ 12,50
Rock Factor	5,29	5,29
Density	1250,0 kg/m3	1250,0 kg/m3
RWS	105	105
Fragmentation Limit	90%	90%

Size	400,0 mm	400,0 mm

This first approach must be treated as any other non-linear problem, considering that this solution can be an optimum local and not the global one. Knowing this, the practical methodology is presented below.

4.4.1 Results

The authors defined a plan to achieve the obtained results in order to avoid too much changes in the terrain and manage the results at every stage. Small changes were applied on each stage and fragmentation results were evaluated. The pattern was expanded until the limits of the desired fragmentation were acceptable. On Table 5 is possible to analyse the evolution on each stage.

Table 5. Field data analysis

	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
(KR Adjusted) X20	70,0 m	72,0 mm	73,0 mm	75,0 mm	76,0 mm	78,0 mm	79,0 mm	81,0 mm	82,0 mm	84,0 mm
(KR Adjusted) X50	149,0 m	156,0 mm	160,0 mm	163,0 mm	165,0 mm	168,0 mm	171,0 mm	173,0 mm	176,0 mm	178,0 mm
(KR Adjusted) X80	263,0 m	279,0 mm	287,0 mm	291,0 mm	294,0 mm	298,0 mm	302,0 mm	305,0 mm	309,0 mm	312,0 mm
(KR Adjusted) X90	335,0 m	356,0 mm	367,0 mm	372,0 mm	376,0 mm	380,0 mm	384,0 mm	388,0 mm	392,0 mm	396,0 mm
(Photo-Analysis) X20	57,50 mm	60,90 mm	53,20 mm	56,00 mm	62,60 mm	64,30 mm	N/A	N/A	N/A	N/A
(Photo-Analysis) X50	136,60 mm	141,50 mm	152,30 mm	149,03 mm	146,20 mm	149,70 mm	N/A	N/A	N/A	N/A
(Photo-Analysis) X80	245,80 mm	258,70 mm	268,30 mm	272,40 mm	275,20 mm	284,90 mm	N/A	N/A	N/A	N/A
(Photo-Analysis) X90	320,80 mm	336,90 mm	343,70 mm	352,50 mm	386,71 mm	**481,53 mm**	N/A	N/A	N/A	N/A

5. CONCLUSION

Analysing Table 5 the authors incremented 10 cm on burden and spacing on each stage. Up to Stage 4 no fragmentation issue, however when the Stage 5 was applied some oversizes were observed (X90 = 481,53mm). The authors took the decision to select the Stage 4 as the "optimum global".

This blast pattern was used to blast 5 020 000 m^3 and, on Figure 8, are presented the Drill and Blast improvements in terms of holes reduction (were estimated a reduction of 2779 holes applying this methodology). In Figure 9 the savings for drilling, explosives and accessories represents an overall saving of 826 019,59€.

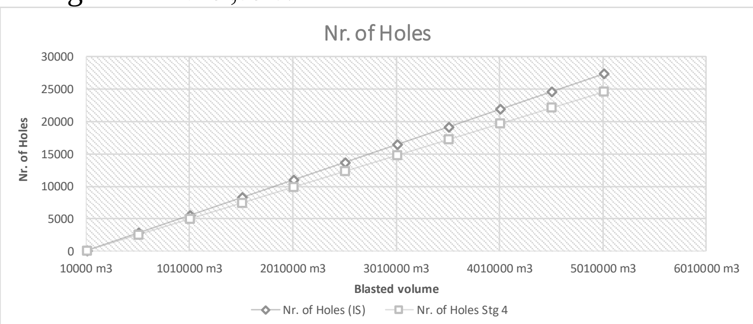

Figure 8. Number of holes evolution (IS vs. Stg4)

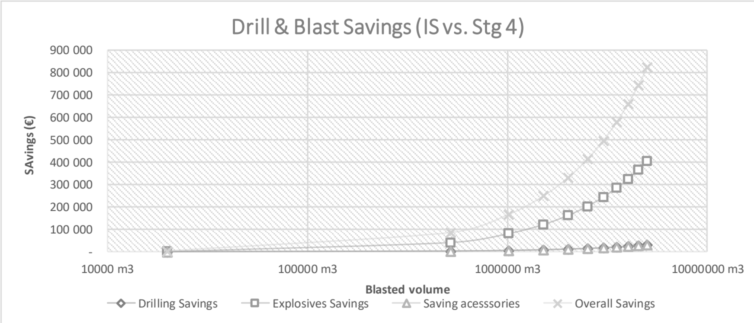

Figure 9. Drill&Blast Savings (IS vs. Stg 4)

The cost benefits and the quality of blast results prove by themselves the utility of this kind of numerical approaches on blast pattern definition. With this research is proved that it's possible to build mathematical models that simulate results for a blast geometric variables. This methodology proved to be very useful in setting strategies for cost reduction and blast optimization. It's always important to combine mathematic models with field experience to avoid excessive changes and end up with productivity and safety issues.

This kind of approaches can be used not only for pattern expansion but also for patter adjustments (sometime closing the pattern) to fulfill mine to mill demands in terms of blast results.

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