Pattern Expansion Optimization Model based on Fragmentation Analysis with Drone Technology

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Abstract

With an increasing pressure to find efficiencies in the mining industry, operations are looking for continuous improvement tools to validate blasting procedures, a crucial and often overlooked area of the process. Using case studies completed at both small and large-scale mining operations, this technical paper proposes a practical method for pattern expansion studies, taking into account terrain parameters, rock quality and explosive strength. This technical paper will use a series of tools geared towards an economical continuous improvement procedure, using UAV particle size analysis to optimize blasting based on "generalized reduced gradient" for non-linear problems, with cost savings being the main objective. For the validation of this methodology, one scenario was created based on the operation's budget: an economical continuous improvement plan that relied on manual data collection methods in order to baseline and optimize procedures.

Introduction

The mining production cycle is represented by two main stages: rock breakage and material handling. The rock breakage process is dependent on drilling and blasting. In general, boreholes are drilled by mobile rotary percussion drills (Figure 1), over the area to be excavated, for the loading of explosives (mainly ammonium-nitrate based) (Hartman, 1992). When the explosive is detonated, high compressive/tensile waves travels through the rock mass followed by high pressure gases. This process reduces the rock mass to fragments capable to be hauled economically.

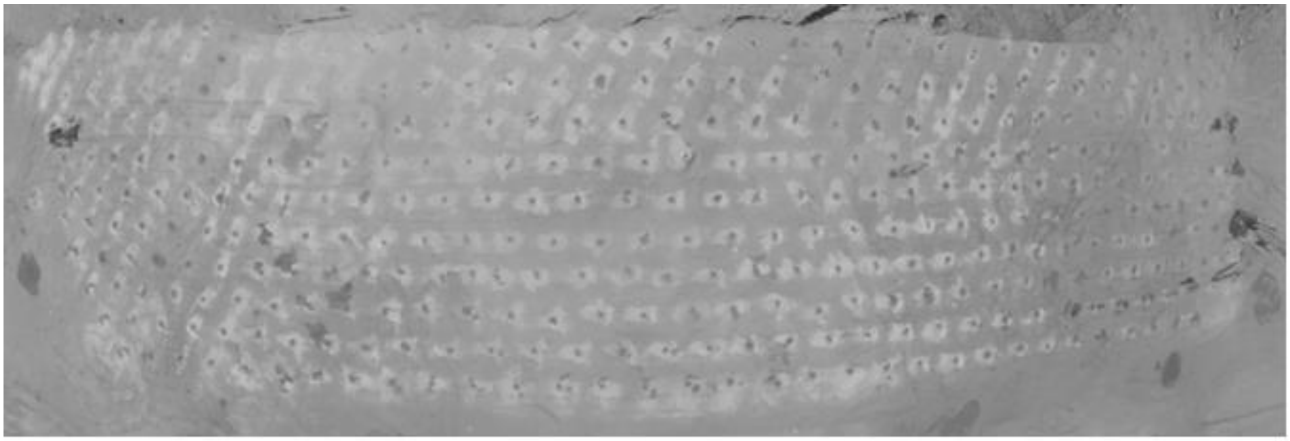


Figure 1. Blast Pattern Drone Control

All modern industries, including mining companies, chase the best operation process to reduce the overall cost and, consequently, increment the profit. In general, mining operation costs are defined by crushing and milling cost, load and haul cost and drilling and blasting cost (Figure 2). The overall cost is the result of the combination of each individual cost and as the drilling and blasting process is the first stage of the operation, it has a great impact on the final score. This document is focused on the optimization of blasting performance to obtain a desired result at a minimum cost possible.

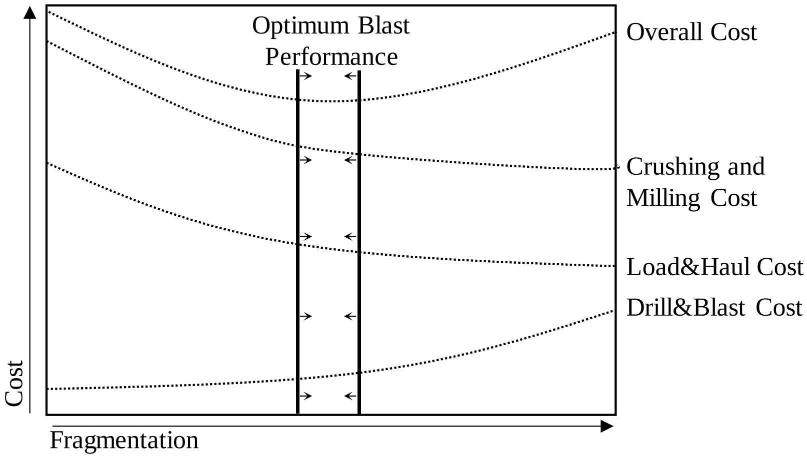


Figure 2. Mining cost relation (adapted from Efficient Blasting Techniques, (Floyd, 2000)

Rock Fragmentation

Fragmentation process

The objective of a blast is to fragment and displace the rock. This stage can have great impacts on loading, hauling, crushing and milling. With the constant need to reduce costs and comminution optimization, several models have been created to estimate fragmentation from blasting. The simplest and widely accepted model is Kuz-Ram (Cunningham, 2005) and is the method selected for this application.

To understand the variables that effect particle size distribution from blasting it is important to consider the well-known physics of rock fragmentation:

- When a rock when subjected to a certain state of pressure is more resistant to compression than when subjected to a tensile stress (Persson, Holmberg, & Lee, 1994).
- When an explosive shock (P) wave hits the borehole walls applies a compressive strength deforming the rock in a perpendicular direction.
- If this compressive strength is higher than the compressive resistance of the rock mass, this will be pulverized/fragmented (borehole hydrodynamic and plastic zone), in the other case, fractures (weak cracks or fissures) will be generated resulted by the lateral deformation of the rock (borehole semi-plastic zone).
- When the compressive wave hits a free face, will be reflected as a tensile wave, deforming the rock perpendicularly to its direction in the same moment that gases at high pressure and temperature start expanding from the borehole center, acting like a wedge in the generated fractures.
- The combination of these two last points generates the fragmentation and movement of the material (Sanchidrián & Muñiz, 2000).

Fragmentation prediction

To predict the degree of fragmentation prior to a blast, an empirical fragmentation model was proposed by Cunningham, 2005 – The Kuz-Ram fragmentation model. The ease of application of 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.

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

Where X_m *= Mean 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-Rammler Equation (Equation 2), represents the size distributions of fragmented rock. It does a very good job characterizing natural rock breakage particle size distributions between 10 and 1000mm (Catasús, 2004, p. 80).

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

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

Uniformity index equation, determines a constant that represent the uniformity of blasted fragments based on the design parameters indicated in Equation 3.

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

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).*

Fragmentation analysis

Fragmentation analysis process (in field)

When referring to blast optimization one of the main key factors are fragmentation results. Rapid and effective measurements are crucial for an accurate and effective continuous improvements on this field (Maerz N. H., 1990). In the present research was used a fragmentation analysis system (WipFrag) for particle size detection. The system uses an automatic algorithm transforming an image into a binary image, identify individual particles and create a border line around each element. This methodology includes several Edge Detection Parameters (EDP) like the use of thresholding and gradient operators in order to delineate the blocks before calculating its area and size (Figure 3) (Maerz, Palangio, & Franklin, 1996).

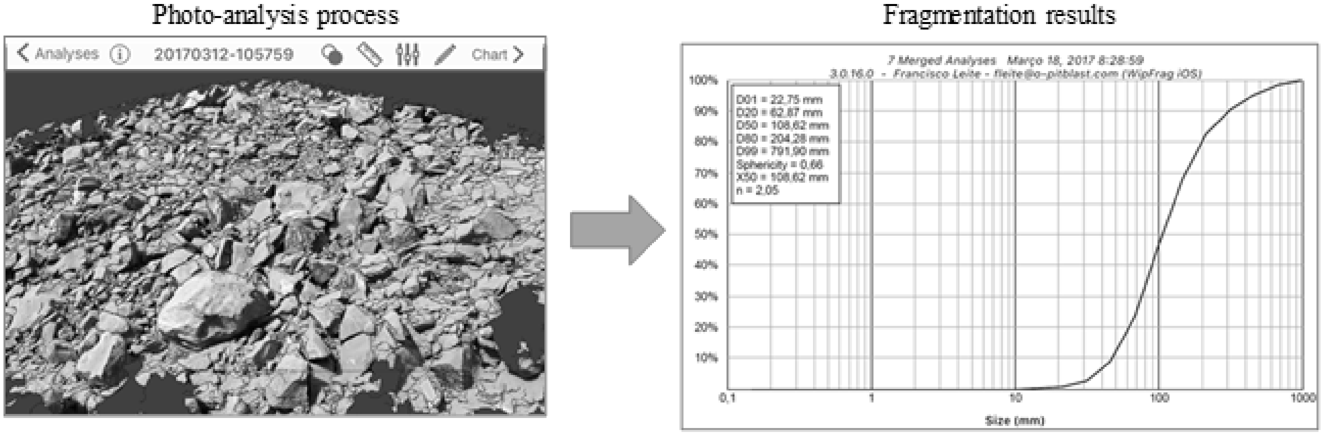


Photo-analysis process

Fragmentation results

Figure 3. Image process and particle size distribution

Drone Technology

A drone, also known as UAV (Unmanned Aerial Vehicle) is an aerial vehicle that does not have a person on board to fly it. In the last years, these vehicles have gained a popularity in other areas like communication, sports, agriculture, remote sensing, pests control, mining (Rathore & Kumar, 2015). In mining, drone technology reduces the manual effort and risks in survey procedures, mapping, misfires inspection, machinery tracking, structures inspections and dilution control. In his case, UAVs are playing an important role in fragmentation analysis reducing the risk associated with muckpile inspection, saving great amounts of time collecting fragment samples and ground-based photographs.

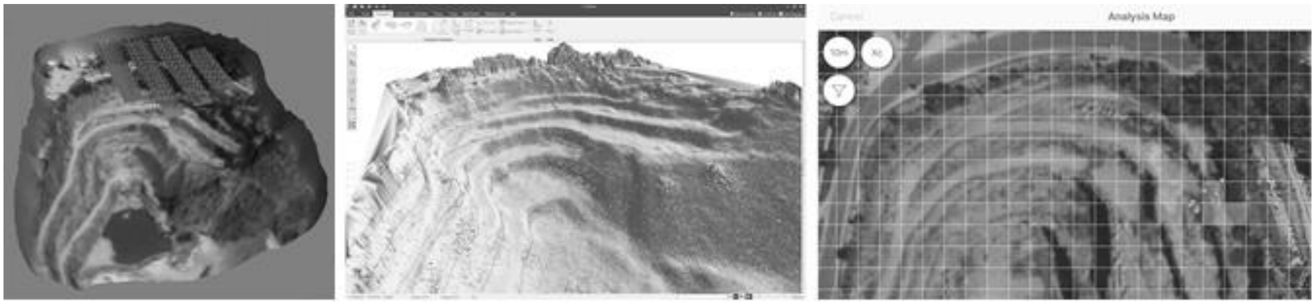


Figure 4. Drone Topography Control and Fragmentation Analysis GIS

Drone Use Tips

Newcomers to the rapidly expanding drone user base should be aware of all drone use regulations in their area. Although many laws are currently in development there are several things that all responsible drone users should observe regardless of the drone size/type or operating location:

- Always operate your drone during daylight hours and keep line of sight of it at all times
- Never operate your drone within 8km (5mi) of a commercial airport or overhead of people
- Always do a pre-flight check for restricted airspace and stay below 120m altitude (400ft)
- It is your responsibility to make yourself aware of any regulations/laws/licenses or certificates necessary to legally operate a drone in your area i.e. FAA Part 107 is required to commercially operate a drone in the USA, many countries have similar regulations.

When configuring a drone to take good quality image samples there are additional operating considerations:

- Use quad rotor camera type drones - other models like racing, fixed wing or toy drones are typically not suitable for this application
- Set the camera angle to 90° (perpendicular to the ground)
- Set the imaging overlap to 80% (reduces optical distortion)
- Plan to fly your mission at noon ±2 hours (minimizes long shadows)
- Set the flight altitude between 30-60m (100-200ft)
- Use autonomous flight modes whenever possible (generates high quality & consistent results regardless of user)
- Collect 50-500 image samples per mission (depends on area size and camera resolution)
- When stitching the drone images into an orthomosaic, ensure the output file type is GEOTIFF
- Use free mobile applications like Hover as a secondary pre-flight check to identify additional risks that may be in your area
- Respect other people’s privacy when operating close to residential areas
- Avoid flying in precipitation, high winds, poor visibility or at night
- Avoid flying near tall structures like power lines, buildings or too close to highwalls

Mathematical Optimization

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 function.

The first objective is to define the involved decision variables. In blasting optimization problems, these variables can be burden, spacing, diameter, bench high and other design parameters. The restriction would be empirical ranges of blasting design parameters and the desired results from a blast, such as fragmentation size limits. The objective function defines the objective of the problem (Taha, 2008); in this case is to obtain the desired results at the lowest cost possible.

In terms of operational research, the authors used the Kuz-Ram model to find the best blast parameters given a certain fragmentation limit and, in this model, all the variables are correlated between each other in a non-additive way. This last characteristic is representative of a non-linear problem, and a non-linear programming technique was used to find the local/global minimum/maximum – Generalized Reduced Gradient. This methodology found the best solution (or a solution close to that) within the variables/parameters combination, respecting the restrictions, that will respect the objective function (Hillier & Lieberman, 2010).

Pattern Expansion Procedure and Results

Pattern expansion is one of the key factors on drill blast cost savings. This procedure can bring high benefits to a mine operation; however, it needs to be simulated and predicted in a blast simulator to avoid field issues like secondary blasting, overbreak, toe and poor fragmentation. Even with the computer simulation, the field work must be staged in a way that every change is sufficiently small to sidestep any operation problem, allowing a sufficient cost saving. This study used an optimization module present in a blast design software in order to calibrate the fragmentation prediction model and estimate the best design parameters.

Blast Design and Actual Results

In general, when a blast engineer intends to optimize a blast, there's a phase of data collecting to define the initial stage and calibrate the prediction models. For the present study, the initial design parameters are presented on Table 1.

Table 1. Initial blast design parameters

Parameter	Value
Burden	3,0 m
Spacing	3,5 m
Diameter	102,0 mm
Stemming	2,8 mm
Sub drill	1,2m
Bench Height	10m
Powder Factor	0,77 kg/m3

Small/Medium Operations – Fragmentation analysis and control with drone technologies

A relatively recent methodology appeared to obtain fragmentation information with a drone flight. In the presented study was used a DJI Phantom 4® and a flight plan was estimated by the DroneDeploy® app. The process is defined in the following steps:

- Define the area to be analyzed;
- Define ground sampling distance and respective height;
- Define the photo overlay (80% in the current study) and camera angle (90°)
- Adjust all the above parameters within the drone's battery limitations.

The result from the drone flight will be a series of georeferenced photos (drone's GNSS receiver precision) which should be processed in a photogrammetry analysis software in order to generate a scaled orthophoto (GEOTIFF). In the market, there are several free and payed solutions, DroneDeploy®, Agisoft Photoscan®, Pix4Dmapper® and MicMac® are some examples.

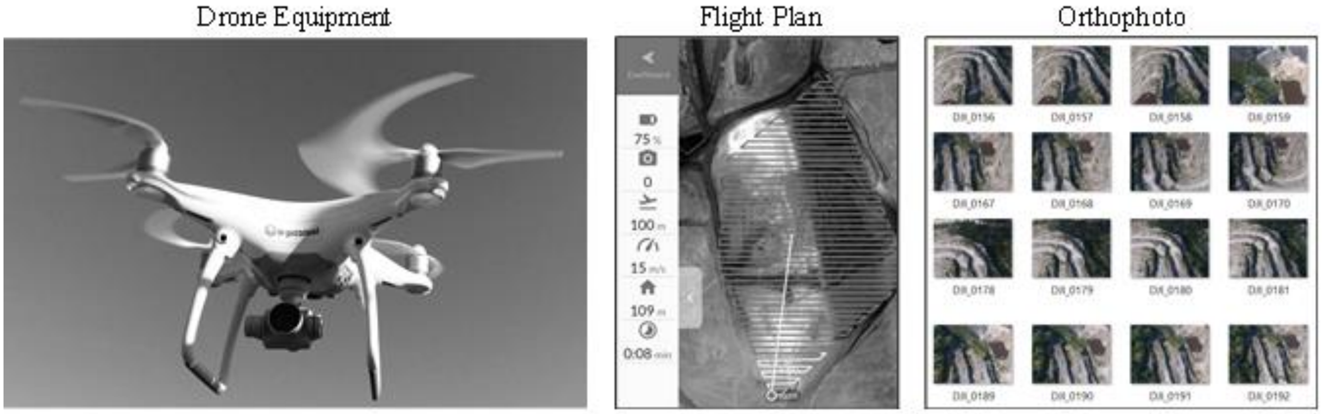


Figure 5. Drone Technology for Fragmentation Analysis

The orthophoto image sample is analyzed in the WipFrag software to generate geographically referenced particle size distribution data. (Figure 6).

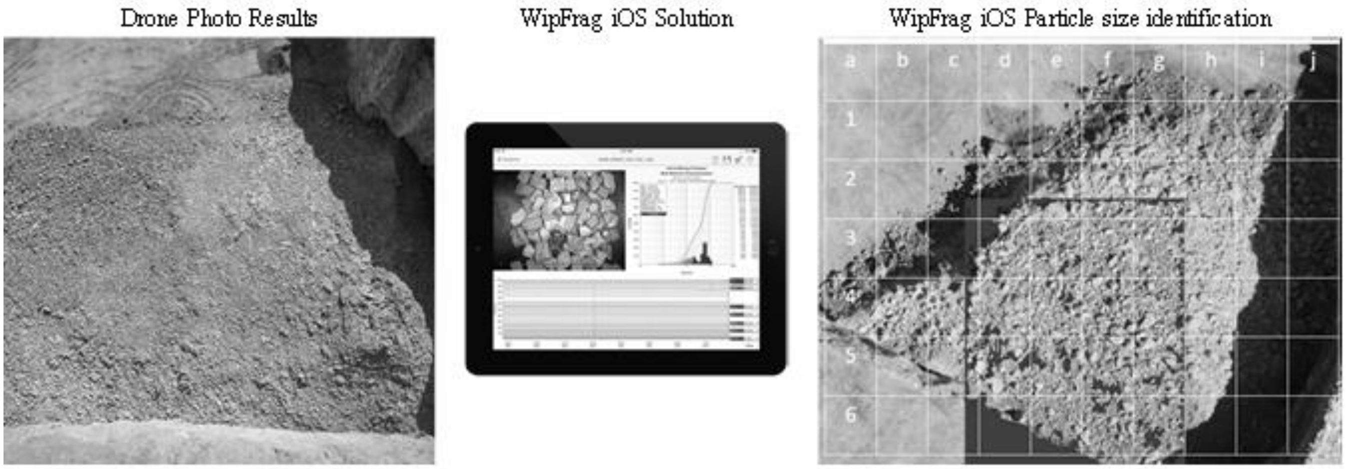


Figure 6. Fragmentation Analysis using WipFrag w/GIS

Large Operations – Automatic fragmentation analysis and control
It should be mentioned that if time/personnel and resources are limited, or if the environment is too extreme or unsafe to employ manual/drone image acquisition then there are completely automated solutions worth considering that are capable of collecting the highest quality, realtime data 24/7/365 even in the most challenging environments.

Figure A. Example of an autonomous and completely automatic fragmentation analysis instruments shown in different configurations

Calibrating Rock Factor

Is imperative to have an actual prediction model before simulating any change on design parameters. For that reason, is important to have the Kuz-Ram's Rock factor calibrated. Table 2 presents the initial state of rock calibration factor, predicted and actual fragmentation. Several blasts were analyzed in order to find the most accurate rock factor. The calibration process used the referred GRG nonlinear programming optimization methodology. The process to calibrate the rock factor/rock influence constant analyzed the predicted and measured X20, X50, X80 and X90 (Figure 3) to obtain a perfect match between the two fragmentation curves. The process is described in Figure 7.

Table 2. Rock factor calibration process

	Initial Parameters	Rock Factor Cal. STG 1	Rock Factor Cal. STG 2	Rock Factor Cal. STG 3
Diameter	102,0 mm	102,0 mm	102,0 mm	102,0 mm
Bench High	10,0 m	10,0 m	10,0 m	10,0 m
Burden	3,0 m	3,0 m	3,0 m	3,0 m
Spacing	3,5 m	3,5 m	3,5 m	3,5 m
Subdrilling	1,2 m	1,2 m	1,2 m	1,2 m
Stemming	2.8 m	2.8 m	2.8 m	2.8 m
(KR Adjusted) X20	91,0 mm	97.0 mm	102,0 mm	106,0 mm
(KR Adjusted) X50	190,0 mm	204,0 mm	213,0 mm	224,0 mm
(KR Adjusted) X80	330,0 mm	353,0 mm	369,0 mm	390,0 mm
(KR Adjusted) X90	416,0 mm	446,0 mm	466,0 mm	493,0 mm
(Photo-Analysis) X20	109,9 mm	114,0 mm	117,8 mm	115,3 mm
(Photo-Analysis) X50	209,6 mm	220,7 mm	225,8 mm	235,9 mm
(Photo-Analysis) X80	347,7 mm	364,5 mm	384,1 mm	399,5 mm
(Photo-Analysis) X90	433,7 mm	457,1 mm	480,7 mm	506,1 mm
Rock Factor Cal.	7	7,5	7,83	8,14

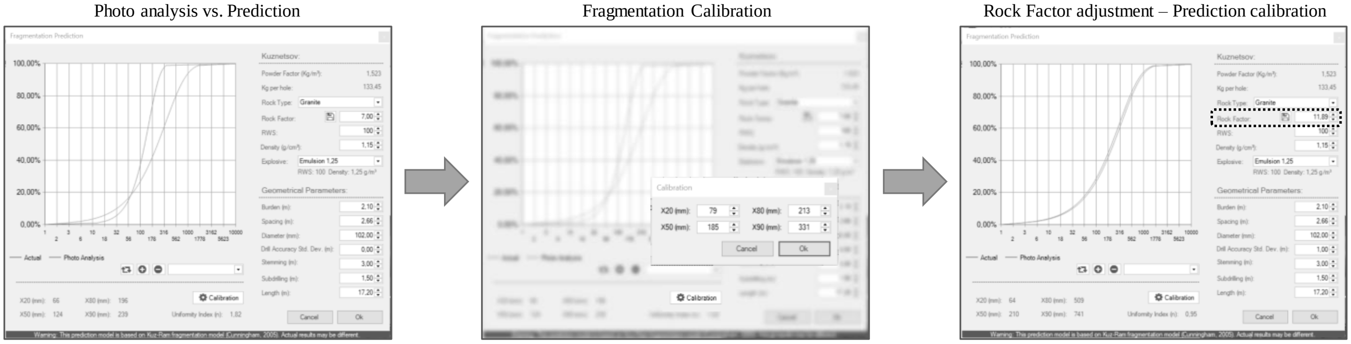


Photo analysis vs. Prediction

Fragmentation Prediction
Kuznetsov:
Powder Factor (Kg/m³): 1,523
Kg per hole: 133,45
Rock Type: Granite
Rock Factor: 7,00
RWS: 100
Density (g/cm³): 1,15
Explosive: Emulsion 1,25
RWS: 100 Density: 1,25 g/m³
Geometrical Parameters:
Burden (m): 2,10
Spacing (m): 2,66
Diameter (mm): 102,00
Drill Accuracy Std. Dev. (m): 0,00
Stemming (m): 3,00
Subdrilling (m): 1,50
Length (m): 17,20
X20 (mm): 66 X80 (mm): 196
X50 (mm): 124 X90 (mm): 239 Uniformity Index (n): 1,82
Warning: This prediction model is based on Kuz-Ram fragmentation model (Cunningham, 2005). Actual results may be different.

Fragmentation Calibration

Calibration
X20 (mm): 79 X80 (mm): 213
X50 (mm): 185 X90 (mm): 331

Rock Factor adjustment – Prediction calibration

Fragmentation Prediction
Kuznetsov:
Powder Factor (Kg/m³): 1,523
Kg per hole: 133,45
Rock Type: Granite
Rock Factor: 11,89
RWS: 100
Density (g/cm³): 1,15
Explosive: Emulsion 1,25
RWS: 100 Density: 1,25 g/m³
Geometrical Parameters:
Burden (m): 2,10
Spacing (m): 2,66
Diameter (mm): 102,00
Drill Accuracy Std. Dev. (m): 1,00
Stemming (m): 3,00
Subdrilling (m): 1,50
Length (m): 17,20
X20 (mm): 64 X80 (mm): 509
X50 (mm): 210 X90 (mm): 741 Uniformity Index (n): 0,95
Warning: This prediction model is based on Kuz-Ram fragmentation model (Cunningham, 2005). Actual results may be different.

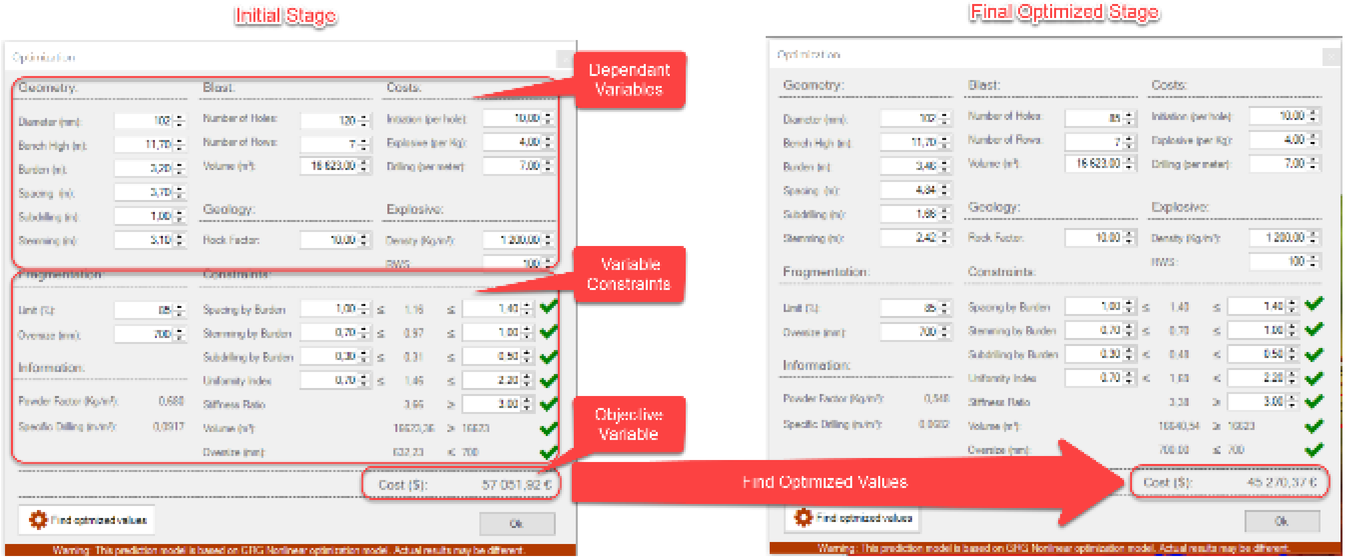
Figure 7. Rock Factor Calibration Process (O-Pitblast system)

Building Optimization Module

To obtain the optimum blast design parameters it is necessary to build a non-linear problem. In other words, define the dependent variables, empirical restrictions and fragmentation demands (90% under 700 mm/27,56 in, in this case). Figure 8 represents the model variables/restrictions and are shown the initial and final/optimized parameters.

This first approach needs to be treated as any other non-linear problem (with its own limitations), considering that this solution can be an optimum local instead of a global one (Miranda, Leite, & Frank, 2017). To avoid any kind of issue the authors defined a field application procedure.

The idea behind the pattern expansion field is to avoid excessive deviations at the same time. Controllable changes were applied at any improvement stage and detailed fragmentation analysis were performed in order to control the blast results. The pattern was expanded until the fragmentation limit was reached. In Table 3 the reader can analyze the evolution of each stage in terms of changes and results.



Initial Stage: Diameter (mm): 102; Bench High (m): 11,70; Burden (m): 3,20; Spacing (m): 3,70; Subdrilling (m): 1,00; Stemming (m): 3,10; Number of Holes: 120; Number of Rows: 7; Volume (m³): 16 623,00; Initiation (per hole): 10,00; Explosive (per Kg): 4,00; Drilling (per meter): 7,00; Rock Factor: 10,00; Density (Kg/m³): 1 200,00; RWS: 100; Oversize (mm): 700; Powder Factor (Kg/m³): 0,688; Cost ($): 57 051,92 €

Final Optimized Stage: Diameter (mm): 102; Bench High (m): 11,70; Burden (m): 3,46; Spacing (m): 4,84; Number of Holes: 85; Number of Rows: 7; Volume (m³): 16 623,00; Initiation (per hole): 10,00; Explosive (per Kg): 4,00; Drilling (per meter): 7,00; Rock Factor: 10,00; Density (Kg/m³): 1 200,00; RWS: 100; Oversize (mm): 700; Powder Factor (Kg/m³): 0,548; Cost ($): 45 270,37 €

Figure 8. Optimization Module

Table 3. Pattern expansion evolutionary stages

	Initial Stage	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Diameter (mm)	102,0 mm	102,00 m	102,00 m	102,00 m	102,00 m	102,00 m
Bench High (m)	10,00 m	10,00 m	10,00 m	10,00 m	10,00 m	10,00 m
Burden (m)	3,0 m	3,1 m	3,1 m	3,2 m	3,3 m	3,3 m
Spacing (m)	3,5 m	3,6 m	3,7 m	3,8 m	3,9 m	4,0 m
Subdrilling (m)	1,2 m	1,2 m	1,1 m	1,1 m	1,0 m	1,0 m
Stemming (m)	2,8 m	2,9 m	3,0 m	3,1 m	3,2 m	3,3 m
(KR Adjusted) X20	105,0 mm	109,0 mm	113,0 mm	117,0 mm	121,0 mm	125,0 mm
(KR Adjusted) X50	221,0 mm	233,0 mm	245,0 mm	257,0 mm	270,0 mm	283,0 mm
(KR Adjusted) X80	383,0 mm	409,0 mm	433,0 mm	461,0 mm	488,0 mm	520,0 mm
(KR Adjusted) X90	484,0 mm	519,0 mm	552,0 mm	591,0 mm	629,0 mm	689,0 mm
(Photo-Analysis) X20	124,5 mm	134,7 mm	151,8 mm	171,2 mm	223,9 mm	N/A
(Photo-Analysis) X50	240,1 mm	275,8 mm	303,4 mm	327,1 mm	352,6 mm	N/A
(Photo-Analysis) X80	398,1 mm	449,9 mm	480,3 mm	517,8 mm	543,1 mm	N/A
(Photo-Analysis) X90	501,5 mm	541,9 mm	604,4 mm	653,8 mm	714,8 mm	N/A

Conclusion

The use of technology to support mining daily tasks is performing an important role in terms of safety and production. The gathering process of field samples with drones, opened a completely new horizon on the fragmentation analysis procedures. Muckpile inspection is associated with several safety issues like gas presence (after blast), twisted ankles and hand injuries.

Fragmentation is one of the primary blast performance indicators. Having a rapid and easy method to quantify blast fragmentation proved to be invaluable to make this continuous improvement effort possible. In terms of mining cost optimization, a blast continuous improvement should be a constant practice since it affects all the consequent stage of mineral processing. With O-Pitblast's blast optimization algorithm was possible to reduce $229,361 in cost 605,307 m3/791,712 yd3 of rock (Figure 9 and Figure 10). The optimization process, operation and field practices demonstrated that a careful analysis must be done in order to match the mathematical optimization and nature behavior to obtain the best and desired results.

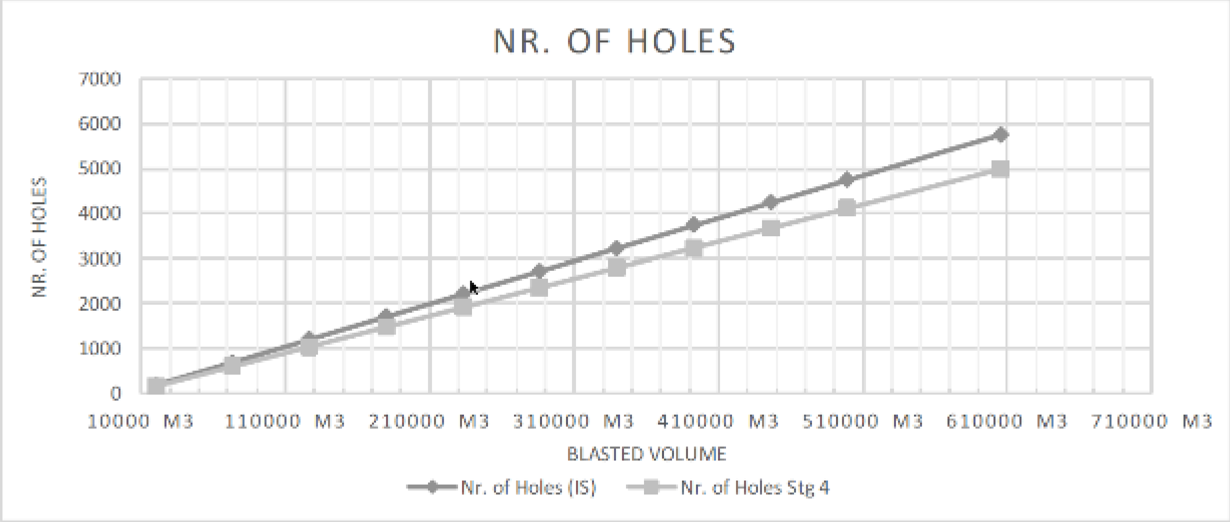


Figure 9. Drilled Holes

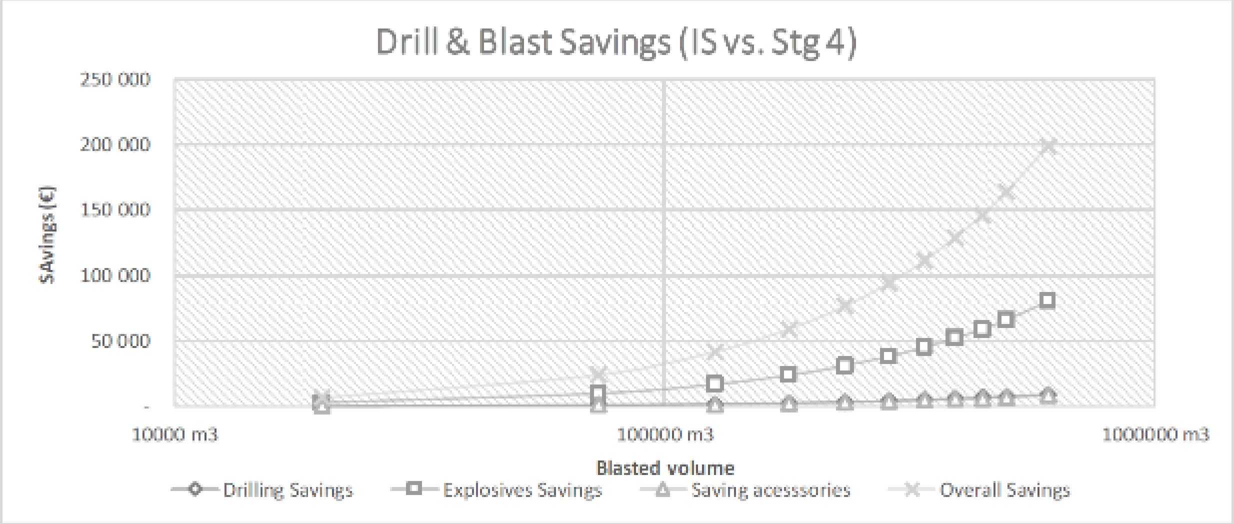


Figure 10. Drill and Blast Savings

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