Drill and Blast in Gypsum Quarries: Optimization of Technical, Economic, and Safety Aspects in "Monte Tondo" Mid-mountain Case Study

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Abstract

Drilling and blasting operations are one of the common deals in open pit mining. Recently, mathematical rigorous patterns are on attention and digitalization and optimization of mining operations are highly suggested. In this work, drilling and blasting operations are modeled and various scenarios are simulated. The usual result of numerical simulations is the fragmentation curve caused by blasting. It is defined as a function of the blasting geometric pattern, the explosives' type and quantity, and the rock-mechanics characteristics. The aim of this work is to improve the blasting efficiency in quarrying, through proper understanding of the fracture mechanisms and optimization of blasting alternatives. The analysis was developed over the Monte Tondo gypsum quarry, owned by Saint-Gobain (joint-stock company in Italy). The case study was modeled by O-Pitsurface®. After model calibration using the in situ quarry data, several optimization hypotheses were developed, starting from the original blasting scheme. Two fragmentation thresholds were applied. First, the minimum dimension of fragmentation to avoid additional breaking, and secondly, the limit of fragmentation dimension for the crushing feed. For each hypothesis, the appropriate parameters were defined. The optimized best hypothesis was finally selected, based on time saving of 145 h/year of work related to drilling and breaking; economic saving of €24,150/year, due to the blastholes numbers' reduction; and finally, improvement of safety conditions by 12%, thanks to lower dimension of fragments which leads to an easier and safer management.

1 Introduction

Blasting for exploiting rocks in mines and quarries is used since the seventeenth century, and was developed based on the advancements of the black powder, discovered in the Middle Ages [1]. The estimation of fragment size distribution for blasted materials is nowadays a crucial discussion in the mining sector, since, for the materials recovery, rock fragmentation is the primary phase, followed by crushing and grinding [2]. The overall economy of every mining activity highly depends on the blasting design. A successful blasting allows to reach the fragmentation targets needed by the beneficiation plants, while blasting failures lead to necessity of re-interventions, with subsequent increase of timing and costs, and also posing serious threats to workers, due to the reduced safety conditions [3].

In minerals production, the blasting design interacts directly or indirectly with the whole mining process, starting from the drilling and excavations machines, the selected areas for loading and hauling, and the subsequent feeding of the crushing plants. Therefore, the result of an effective blasting operation leads to the efficiency of the subsequent stages of the mining operation. Blasts are highly influenced by the rock mass variations, and each design must be tailored to the specific geological and hydrogeological context [4]. In blasting, some parameters can be controlled and managed by operators (mainly, the blast design factors and the explosive characteristics) [5]. On the contrary, other parameters are uncontrollable, and must be known in details by geologists.

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They are the rock properties, the geology of the deposit, the presence of water, and the information about joints [6]. The correct modeling of the blasting system, merging and integrating the controllable and uncontrollable information, allows the engineers to optimally design the blasts, always keeping in mind the fragmentation targets [7].

Several studies on fragmentation prediction have accounted for managing both controllable and uncontrollable parameters. Kuznetsov developed a mathematical equation based on the relationship between the mean fragment size and the specific charge [8]. Cunningham used the Rosin and Rammler distribution function and the Kuznetsov model to develop a new model (Kuz-Ram) to predict rock fragmentation curve by blasting [9]. The model was later improved in 1987 [10]. Other modifications of the Kuz-Ram later appeared. Otterness et al. correlated blast design parameters to estimate materials size after blasting [11]. Kou and Rustan presented an empirical model for estimating the mean fragment size [12]. Lownds predicted fragmentation by using explosive energy distribution [13]. Aler estimated blast fragmentation using a multivariate analysis procedure [14]. Djordjevic modeled blast fragmentation using two failure mechanisms [15]. Chakraborty et al. used multivariate analysis measures for predicting the sizes of muck-pile resulting from fragmentation [16]. Morin and Ficarazzo employed Monte Carlo simulation to predict fragmentation based on the Kuz-Ram model [17]. Gheibie et al. sought to improve fragmentation estimation by modifying the Kuz-Ram model [18].

Kulatilake et al. developed a mean particle size prediction model using neural networks [19]. Monjezi et al. used artificial neural networks to estimate muck-piles size distribution using fuzzy logic [20]. Kulatilake et al. developed a multivariate fragmentation-trained neural network model [21]. Faramarzi et al. used the rock engineering system (RES) approach to predict fragmentation results using geometric properties [22]. Akbari et al. investigated the effect of rock mass properties, blast design parameters, and explosive properties on blast fragmentation [23]. Nizkad et al. used blasting indexes to combine rock geological properties with blast design and consequently designed blast patterns [24]. Hasanipanah et al. used again the RES method to assess the fragmentation risk. They predicted that 80% of muck-pile fragmental materials had low dimension, using geometric parameters [25]. Sanchidrian and Ouchterlony estimated blast fragmentation with a neural network [26]. Jug et al. developed a model to determine the calibrated value of rock factor based on the heterogeneity of the rock to attain the chosen fragmentation of the blasted rock [27]. Ouchterlony et al. predicted percentile fragment size for blasted-induced fragmentation with the aid of an energy fan. [28]. Inanloo Arabi Shad et al. investigated rock blast fragmentation using in situ block size and explosive energy [29]. Hoseini et al.

evaluated blast efficiency by calculating fragmentation degree and assigning a dimensionless value to each blast by employing a general criterion method [30]. Amaoko et al. worked on the evaluation of the Kuz-Ram model as a relevant tool for fragmentation prediction [31]. Monjezi and Dehghani used neural networks to evaluate the amount of backbreak induced by blasting [32]. Miao et al. performed the support vector machine regression model over an existing muck-pile to evaluate its accuracy in predicting the rock fragmentation. Results were satisfying, but very site-specific [33].

Gebretsadik et al. compared the use of various machine learning techniques, including artificial neural networks, support vector machine regressions, random forest regression, and extreme gradient boosting, to explore the relationship between rock fragmentation and the various blasting parameters. They performed the analysis on 219 datasets and they restricted the evaluation, by removing some of the parameters. Results were promising, but highly conditioned by the number and type of available datasets [34]. Generally speaking, the research on fragmentation prediction and blasting optimization will benefit from adding datasets and parameters to the analyses.

All the presented fragmentation prediction models have one or more deficiencies, such as being site-specific, excluding one or more of the parameters affecting mean fragment size and being unable to account for complex geological variability. The variables influencing the rock fragmentation results are numerous. Among all models, the improved Kuz-Ram method is the most accepted because it accommodates more parameters.

The recent challenge is how to adapt the improved Kuz-Ram model to the topographical, geological, and blast design setting of each mine and quarry operations. In recent years, some blasting software such as O-Pitsurface® have undertaken this task, and now the fragmentation can be predicted. Moreover, other parameters are considered within the software such as the different free faces, the blasting pattern design, the imposed delays, and overall the mutual interactions among blasts of single blastholes [35]. On the other hand, some deficiencies in such fragmentation modeling are still present, especially when tackling the geological variability of the blasted area. At the present moment, O-Pitsurface® allows to assign one only rock type (with its properties) to the whole rock mass targeting for blasting. For simple and stable geologies, such approximation is considered to be valid [36]. In other cases, probability and sensitivity analyses must be conducted.

This paper presents the blasting optimization strategy, by using the modified Kuz-Ram model implemented in O-Pitsurface®, conducted over a gypsum open pit quarry in Emilia-Romagna region, Italy. The stable geological conditions allowed to use the Kuz-Ram approximation. However,

a detailed rock mass analysis was conducted in the lab and at the site, in order to quantify the uncertainty degree of the rock factor. Sensitivity analyses allowed to define the potential error of the blasting optimization strategies due to geological variability. Results showed how the numerical modeling can be helpful to optimize the blasting works when the probabilistic effects are properly managed, and by reducing time, costs and increasing the safety conditions.

2 Materials and Methods

2.1 Case Study: Drilling and Blasting at "Monte Tondo" Gypsum Quarry

The gypsum quarry "Monte Tondo" is located in Emilia-Romagna, between Bologna and Ravenna, comprised between the coordinates: latitude 44° 12′ 49″–44° 17′ 31″ N, longitude 11° 30′ 29″–11° 47′ 09″ E, and occupies around 374,500 m^2. The mountain peak is about 436.5 m, while the current gypsum exploitation extends from 200 to 320 m. The quarry is located besides the "Gypsum Vein of Romagna" Regional Park, an area classified as *Unesco natural world heritage* in 2023, and so it is subjected to strict environmental rules and controls.

The gypsum grade highly varies in the area, differently according to the geological strata. The ones with the highest grades (up to 90%) are the ones numbered *III*, *IV*, *V*, and *VI* (Fig. 1).

There are 16 exploitation benches, with the 10 m height as the majority (13 levels have 10 m height). The width of each bench is minimum 5 m and the average bench inclination from the horizontal is 66°. The exploitation materials are made by drill-and-blast technique. The blasted materials are sent to a crusher and afterwards loaded on dumpers towards the processing plant located nearby.

The blasting contents include two emulsions (one for the column charge and one, stronger, at the blasthole bottom, acting as the booster), one detonating cord and an electric detonator. The drilling pattern is generally composed by 7 to 15 blastholes disposed on one line. The drilling diameter is 95 mm, and the blasthole inclination from the vertical is 24°, thus parallel to the benches. The burden is 3.8 m, while the spacing is 3.5 m. The ratio between burden and spacing is then 1.1. The blastholes exceed 1 m of the bench height; therefore, their length is 16 m for most of the benches. The delay among blasts is 25 ms.
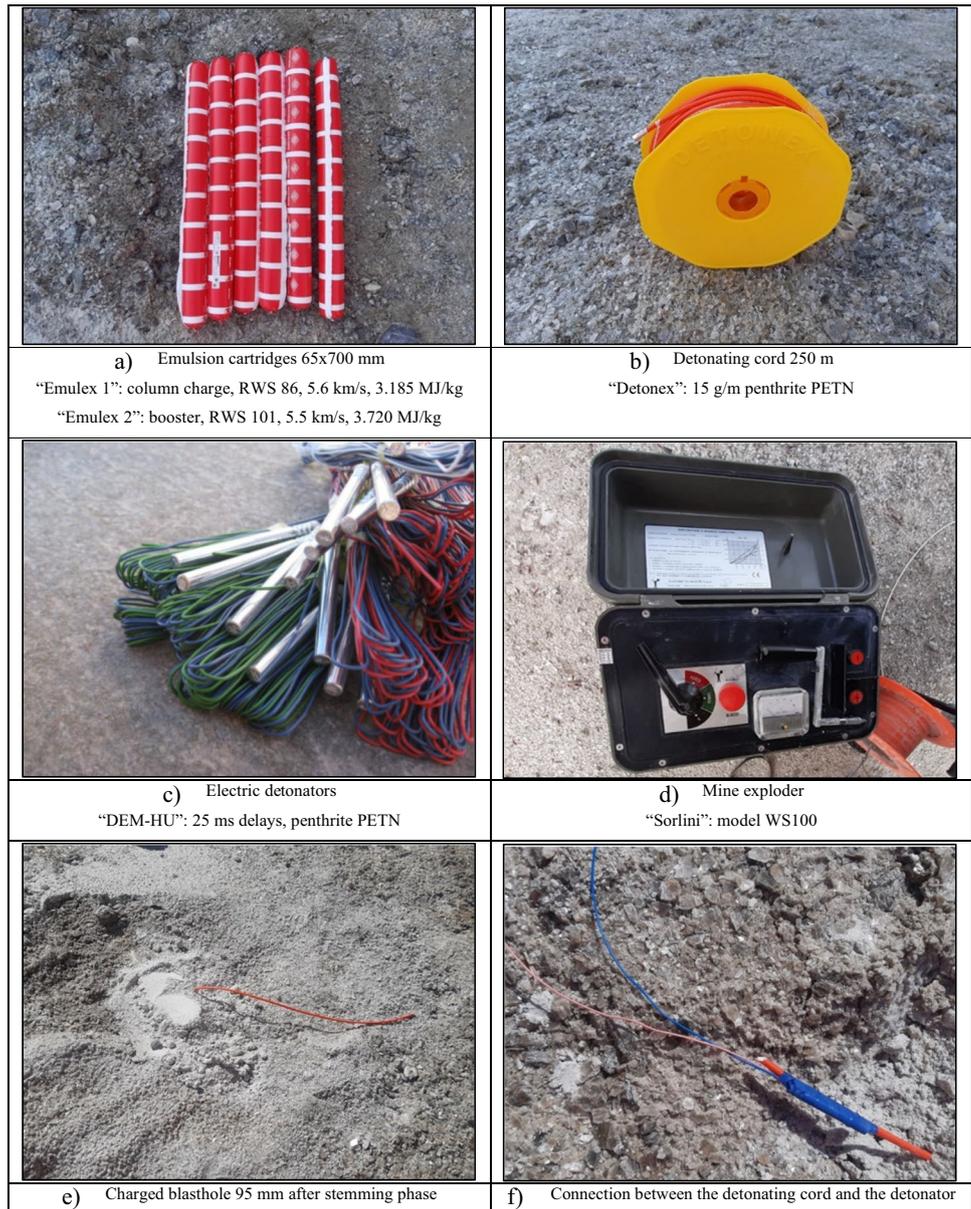
Figure 2 reports all the materials used for blasts and the blasthole details.

The blasting pattern model in O-Pitsurface® has been created based on three specific blasts conducted between March and June 2023. Table 1 reports the features of each blast.

Fig. 1 Monte Tondo gypsum quarry and geological strata with highest grades

Fig. 2 Blasting materials used in the Monto Tondo quarry and the details of connections

a) Emulsion cartridges 65x700 mm
"Emulex 1": column charge, RWS 86, 5.6 km/s, 3.185 MJ/kg
"Emulex 2": booster, RWS 101, 5.5 km/s, 3.720 MJ/kg

b) Detonating cord 250 m
"Detonex": 15 g/m penthrite PETN

c) Electric detonators
"DEM-HU": 25 ms delays, penthrite PETN

d) Mine exploder
"Sorlini": model WS100

e) Charged blasthole 95 mm after stemming phase

f) Connection between the detonating cord and the detonator

Table 1 Blasts used as a benchmark for the model realization

No	Date	Bench altitude (m)	No of blastholes	Blasthole length (m)	Blasthole angle (°)	Spacing (m)	Burden (m)
1	24.03.2023	290	7	13	24	3.5	3.8
2	07.04.2023	300	14	16	24	3.5	3.8
3	01.06.2023	290	12	13	24	3.5	3.8

2.2 The Fragmentation Prediction Model

The classical fragmentation prediction model is based on the Kuznetsov Eq. (1973) [8]:

$$\overline{X} = A \cdot \left(\frac{V_0}{Q_E} \right)^{\frac{4}{5}} \cdot Q_E^{\frac{1}{6}} \cdot \left(\frac{115}{RWS} \right)^{\frac{19}{30}} \tag{1}$$

where $\overline{X}$ is the fragments' average dimension (cm), A is the rock factor, V_0 is the volume of blasted rock (m³), Q_E is the weight of the explosive (kg$_f$), and RWS is the relative weight strength, ratio between the explosive and that of the reference ANFO.

The ratio between the weight of the explosive and the volume of blasted rock is also called specific charge K (kg$_f$/m³).

$$K = \frac{Q_E}{V_0} \tag{2}$$

Therefore, by setting up a target of fragments' dimension, the necessary specific charge can be calculated for each blast.

$$K = \left[\frac{A}{\overline{X}} \cdot Q_E^{\frac{1}{6}} \cdot \left(\frac{115}{RWS} \right)^{\frac{19}{30}} \right]^{\frac{5}{4}} \tag{3}$$

The rock factor depends on many rock mass parameters: the rock mass description RMD, the joints factor JF, the rock density index RDI, and the hardness factor HF.

$$A = 0.06 \cdot (RMD + JF + RDI + HF) \tag{4}$$

Generally, the rock factor A can vary from 5 (very soft rocks) to 12 (very hard and compacted rocks).

By knowing the specific charge K and the rock factor A, the particle size distribution (PSD) can be predicted by targeting the characteristic dimension of the fragments in the Rosin–Rammler distribution (1933)

$$R = e^{-\left(\frac{X}{X_c} \right)^n} \tag{5}$$

where R is the percentage of hold fragmented material for each dimension X, X_c is the characteristic dimension of fragments (cm), and n is their uniformity index.

Therefore, it is possible to get X_c, by imposing R as 50%, corresponding to $\overline{X}$.

$$X_c = \frac{\overline{X}}{\ln \left(\frac{1}{0.5} \right)^{\frac{1}{n}}} \tag{6}$$

The uniformity index n for the specific case of blasting in open pit quarries is object of discussion; however, the equation proposed by Cunningham is generally accepted (1987) [9, 10].

$$n = \left(2.2 - 14 \cdot \frac{B}{D_E} \right) \cdot \left(\frac{1 + \frac{S}{B}}{2} \right)^{\frac{1}{2}} \cdot \left(1 - \frac{W}{B} \right) \cdot \left(\frac{|BCL - CCL|}{L} + 0.1 \right)^{0.1} \cdot \frac{L}{H} \tag{7}$$

where B is the burden (m), D_E is the blasthole diameter (mm), S is the spacing, W is the blasthole deviation (m), L is the charged blasthole length (m), H is the bench height (m),

BCL is the bottom charge length, which generally means the booster length (m), and CCL is the column charge length (m).
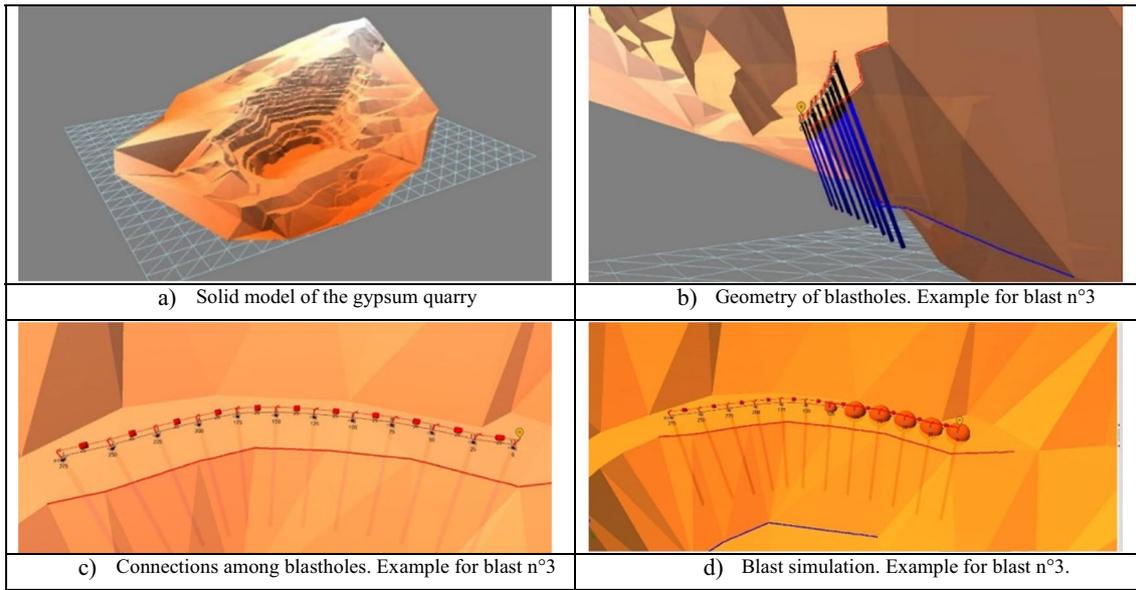
The integration of the different equations presented above is generally known as the Kuz-Ram model. It uses geometry approximations, related to the regular spacing among blastholes, the full homogeneity of all charges in the blast scheme, and the uniformity of the bench. Moreover, various simplifications related to the rock mass properties with respect to real natural conditions are generally applied. The application of the procedure on realistic quarry benches, such as the case study of the present work, is possible but there is the need of inserting all the geometrical and object features and variations inside the blast scheme. It can be nowadays performed through numerical modeling and the use of appropriate software.

2.3 Numerical Modeling and the Blasting Model Calibration

The numerical modeling has been created on the software O-Pitsurface®. First of all, the topography has been reproduced by inserting the Digital Terrain Model (DTM) relating to 2023. The DTM has been created by Delaunay triangulation (Fig. 3a). Afterwards, the three blasthole schemes, presented in Table 1, were reproduced on the model (Fig. 3b), with proper charges, detonating types and delays (Fig. 3c) according to the details presented in Fig. 2. Burden and spacing were defined for the creation of the blasting pattern, ensuring consistent distances between the holes. Each borehole is associated with a vector for burden and spacing that can be adjusted if necessary. The length of these vectors is determined using the Euclidean distance, calculated from the borehole's coordinates to the desired final position of the vector on the terrain. The blasts were then simulated for all the three alternatives (Fig. 3d) in order to obtain a fragmentation result to be compared with the actual values reported by the quarry personnel. The calibration of the model based on the three blasting alternatives was mostly performed manually, since the automatic calibration of the software led to blasting schemes too different from the real drilling patterns and charges used by the quarry.
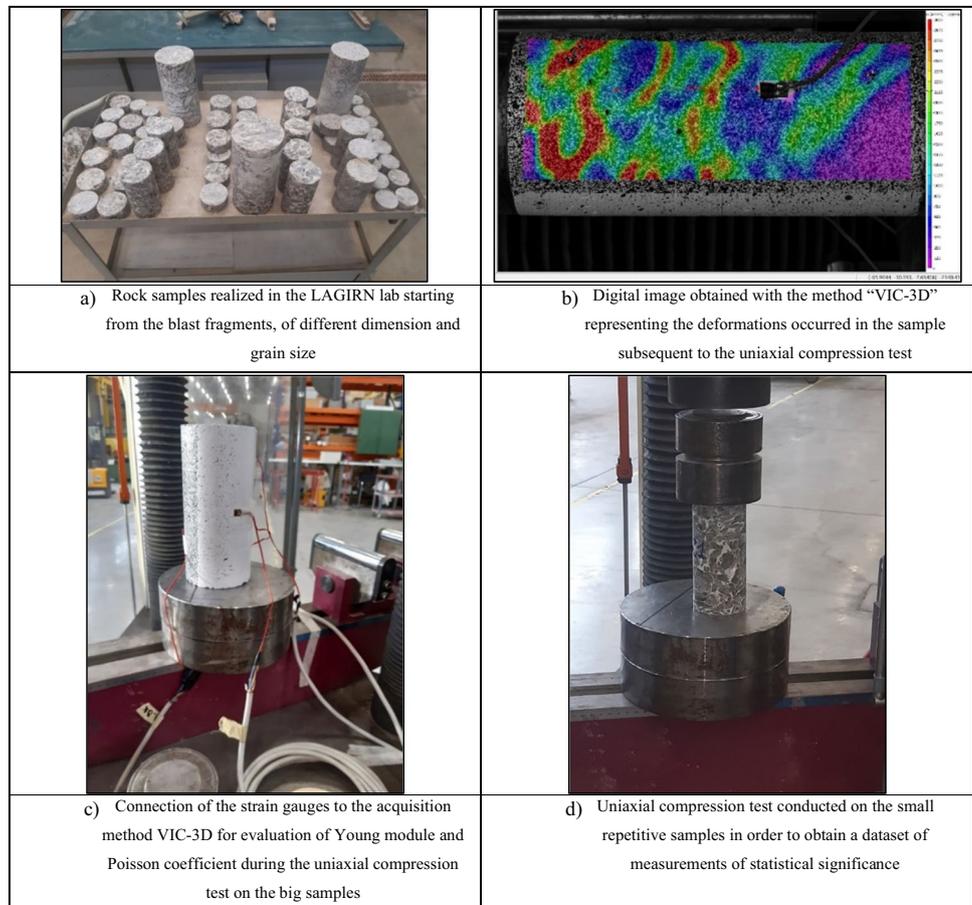
The possible variables to be modified were basically the rock matrix parameters and some of the charging parameters, such as the packing factor, or the quality of stemming [37]. By inserting all the obtained geomechanical information, it was possible to define a rock factor equal to 6, typical for soft rocks (as gypsum is).

The geomechanical information was obtained by historical data. Moreover, new measurements on blast fragments were made in the Geoengineering and Natural Resources lab of Bologna University (LAGIRN), while

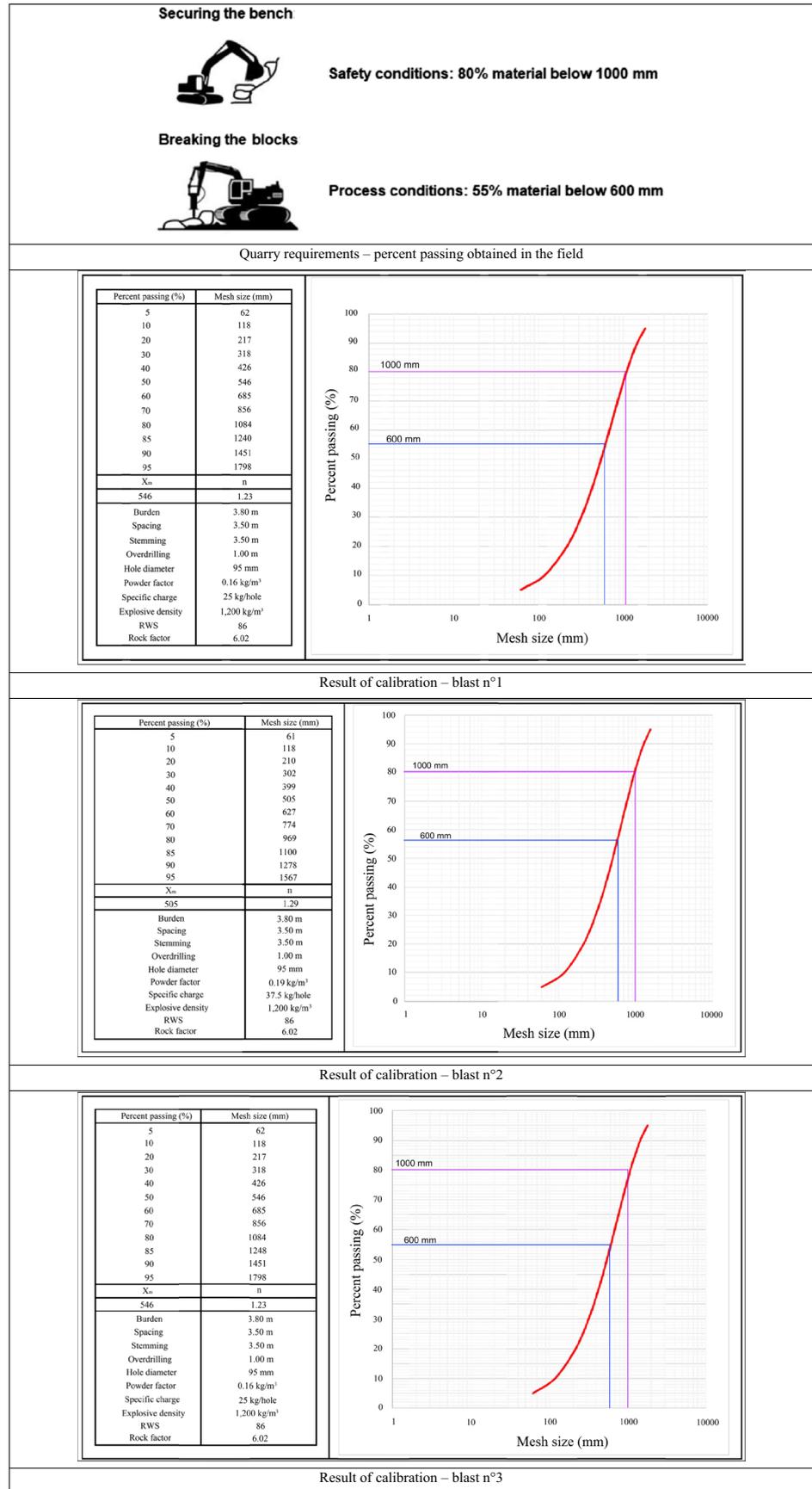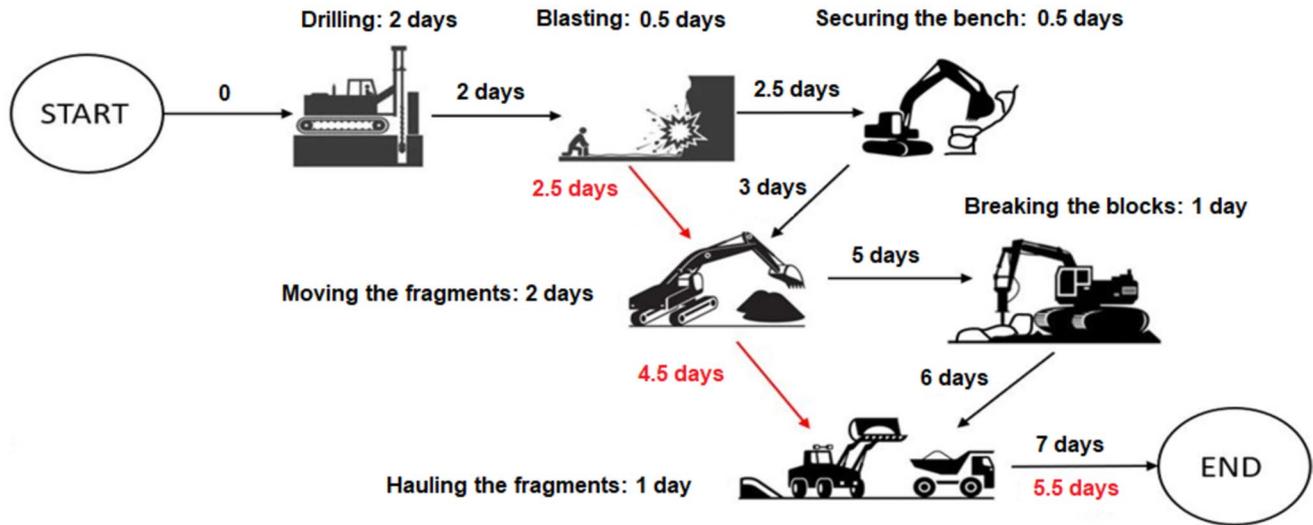| a) Solid model of the gypsum quarry | b) Geometry of blastholes. Example for blast n°3 |
| c) Connections among blastholes. Example for blast n°3 | d) Blast simulation. Example for blast n°3. |

Fig. 3 Blasting model realization with the O-Pitsurface® software

Fig. 4 Photo gallery of the tests conducted on the samples obtained from the blast fragments

| a) Rock samples realized in the LAGIRN lab starting from the blast fragments, of different dimension and grain size | b) Digital image obtained with the method "VIC-3D" representing the deformations occurred in the sample subsequent to the uniaxial compression test |
| c) Connection of the strain gauges to the acquisition method VIC-3D for evaluation of Young module and Poisson coefficient during the uniaxial compression test on the big samples | d) Uniaxial compression test conducted on the small repetitive samples in order to obtain a dataset of measurements of statistical significance |

Fig. 5 Results of the calibration for the three blasts, in line with the fragmentation measurements

Fig. 6 Current process of the Monte Tondo gypsum quarry, with potential time savings due to blasting optimization

specific on-site surveys allowed to obtain an indication of the fractures and discontinuities of in situ rocks.

Tests were done on rock fragments (around 500-mm dimension) from the blasting of June 2023. In the LAGIRN lab, 30 samples have been obtained, which 11 of them had coarse grain, 10 medium grain, and 9 fine-grained.

Uniaxial compression strength has been conducted on 6 coarse grain samples, on 5 medium grain samples, and 4 fine-grained samples [38].

Three samples of bigger dimension (fine, medium, and coarse grain) were chosen for calculating the Young module and Poisson coefficient. This was possible by applying strain gauges on the samples before the uniaxial compression strength test. Moreover, the digital image correlation method "VIC-3D" was used to compare the deformations before and after the uniaxial compression strength test.

The average values of the obtained results have been used for the numerical model on the O-Pitsurface® software. Some photos of the LAGIRN lab tests are reported in Fig. 4.

The calibration results are presented below, in line with the information provided by the blasts measurements. After each blast, the size of bigger fragments was measured with a metric tape. It was possible then to identify the percentage of fragments which need further breaking with demolition hammer. Moreover, the fragments not completely separated from the rock mass were identified for further treatment, in order to secure the working site. In total, only 5% by weight of the whole blasted materials have the dimension bigger than 1800 mm, while around 20% had dimension bigger than 1000 mm. On the other hand, around 45% of the fragments have a dimension bigger than 600 mm and the average dimension is always around 550 mm Fig. 5.

Table 2 Quantity of excavated materials and actual time and costs of operations

Blasting actual result (17 months 01.01.2022–31.05.2023)	Value	Unit
Fragmented gypsum	247,831	t
Percent passing less than 600 mm	54	%
Fragmented material bigger than 600 mm	114,002	t
Jackhammer use	782	h
Jackhammer hourly production	146	t/h
Hourly cost of jackhammer	160	€/h
Total blasthole cost	380	€/bh
Average time for blasthole realization	1.33	h/bh

Table 3 Optimizations proposed involving the charging

Charging	Description
0 (current)	Use of Emulex 1. 8 cartridges for blastholes. 3.5 m stemming
1	Use of Emulex 5. 8 cartridges for blastholes. 3.5 m stemming
2	Use of Emulex 1. 9 cartridges for blastholes. 3.0 m stemming
3	Use of Emulex 5. 9 cartridges for blastholes. 3.0 m stemming

Table 4 Technical details of the Emulex 5 cartridges and comparison with the current Emulex 1

Parameter	Emulex 1 (current)	Emulex 5
Length (mm)	700	700
Diameter (mm)	65	65
Weight (kg$_f$)	3.125	3.125
Density (t/m^3)	1.15	1.15
RWS	86	100
Detonating velocity (km/s)	5.6	5.0
Effective energy (MJ/kg)	3.155	3.698

Table 5 Blasting schemes alternatives to the current one (0)

Blasting scheme	Burden	Spacing
0 (current)	3.80	3.50
1	3.10	4.50
2	3.00	4.60
3	3.10	5.00
4	3.00	5.10

The results from the actual blasting in the gypsum quarry have allowed the normal exploitation operations. It is true that the current operations are slowed due to the biggest fragments for about 1.5 days for each blast. This additional time is needed to secure the bench and to break the biggest blocks, for the safe loading and hauling.

The current process is exemplified in Fig. 6.

The model has been then calibrated over the quarry real operation. Afterwards, the optimization phase began. The optimization module provided by the O-Pitsurface software was preliminarily tested [39], but it was not possible to include all the many constraints given by the quarry (most of all, the type of explosives used, which could not deviate too much from the original one, for cost and market reasons); therefore, a manual approach was adopted. Then, various configurations were tested, to check suitable alternatives to the standard blasthole practice of the gypsum quarry. The configuration tests have been done in order to improve the fragmentation curve and try to reduce the time losses due to securing the bench and breaking the bigger blocks by using demolition hammer. All optimization scenarios considered not increasing the drilling time and neither the costs of explosive materials. The main constraint of such optimization is geometrical: the quarry geometry and scheme and the width of the benches cannot be changed; therefore, each alternative blast must be designed over one only line of blastholes respecting the available dimensions.

The objective grain sizes for Monte Tondo exploitation are basically two:

- 600 mm: maximum dimension for the fragmented material entering the crusher
- 1000 mm: maximum dimension for guaranteeing the safety of operations and especially for moving, loading, and hauling the fragmented material

All fragmented materials with diameter bigger than 600 mm must be treated with the jackhammer, and this will affect the excavation procedures and materials managements. Moreover, the risks for the quarry operators must be limited as much as possible. Due to the weight of the gypsum (the

Table 6 Index used for evaluation of the quality of the optimization and comparison among alternatives

Index	Symbol	Unit	Description
Time saving index	*TSI*	h / t	It considers the saved (or wasted) hours for the drilling operations and for securing the bench and blocks blasting, with respect of a ton of blasted gypsum rock
Cost saving index	*CSI*	€ / t	It considers the total cost savings (or losses) for blasting a ton of gypsum rock
Safety upgrade index	*SUI*	% / t	It considers the percent reduction (or increase) of fragments with dimension higher than 1 m, with respect of a ton of blasted gypsum rock

Table 7 Assignment scores for the quality matrix

Index	Lag	Positive score	Negative score
Time saving index TSI	0.0001 h / t	+ 1 for each time saved lag	− 1 for each time wasted lag
Cost saving index CSI	0.01 € / t	+ 1 for each cost saved lag	− 1 for each cost losses lag
Safety upgrade index SUI	1% / t	+ 1 for each percent reduction lag	− 1 for each percent increase lag

Table 8 Nineteen alternative scenarios compared to Business as Usual

Scenario	Charging	Blasting scheme
Business as usual scenario (0)	Use of Emulex 1 8 cartridges for blastholes 3.5 m stemming	Burden 3.80 m Spacing 3.50 m
Alternative 1	Use of Emulex 1 8 cartridges for blastholes 3.5 m stemming	Burden 3.10 m Spacing 4.50 m
Alternative 2	Use of Emulex 1 8 cartridges for blastholes 3.5 m stemming	Burden 3.00 m Spacing 4.60 m
Alternative 3	Use of Emulex 1 8 cartridges for blastholes 3.5 m stemming	Burden 3.10 m Spacing 5.00 m
Alternative 4	Use of Emulex 1 8 cartridges for blastholes 3.5 m stemming	Burden 3.00 m Spacing 5.10 m
Alternative 5	Use of Emulex 5 8 cartridges for blastholes 3.5 m stemming	Burden 3.80 m Spacing 3.50 m
Alternative 6	Use of Emulex 5 8 cartridges for blastholes 3.5 m stemming	Burden 3.10 m Spacing 4.50 m
Alternative 7	Use of Emulex 5 8 cartridges for blastholes 3.5 m stemming	Burden 3.00 m Spacing 4.60 m
Alternative 8	Use of Emulex 5 8 cartridges for blastholes 3.5 m stemming	Burden 3.10 m Spacing 5.00 m
Alternative 9	Use of Emulex 5 8 cartridges for blastholes 3.5 m stemming	Burden 3.00 m Spacing 5.10 m
Alternative 10	Use of Emulex 1 9 cartridges for blastholes 3.0 m stemming	Burden 3.80 m Spacing 3.50 m
Alternative 11	Use of Emulex 1 9 cartridges for blastholes 3.0 m stemming	Burden 3.10 m Spacing 4.50 m
Alternative 12	Use of Emulex 1 9 cartridges for blastholes 3.0 m stemming	Burden 3.00 m Spacing 4.60 m
Alternative 13	Use of Emulex 1 9 cartridges for blastholes 3.0 m stemming	Burden 3.10 m Spacing 5.00 m
Alternative 14	Use of Emulex 1 9 cartridges for blastholes 3.0 m stemming	Burden 3.00 m Spacing 5.10 m
Alternative 15	Use of Emulex 5 9 cartridges for blastholes 3.0 m stemming	Burden 3.80 m Spacing 3.50 m
Alternative 16	Use of Emulex 5 9 cartridges for blastholes 3.0 m stemming	Burden 3.10 m Spacing 4.50 m
Alternative 17	Use of Emulex 5 9 cartridges for blastholes 3.0 m stemming	Burden 3.00 m Spacing 4.60 m
Alternative 18	Use of Emulex 5 9 cartridges for blastholes 3.0 m stemming	Burden 3.10 m Spacing 5.00 m
Alternative 19	Use of Emulex 5 9 cartridges for blastholes 3.0 m stemming	Burden 3.00 m Spacing 5.10 m

density is between 2.2 and 2.3 t/m^3), any fragment larger than 1000 m can be very dangerous to be managed.

The total quantity of materials and the related actual time costs are reported in Table 2.

The proposed optimization is based on the following alternatives for charging, with respect to the current one (0) in Table 3.

The technical details of the Emulex 5 cartridges are reported in Table 4.

The Emulex 5 has relative weight strength (RWS) and effective energy higher than Emulex 1; therefore, it gives the possibility to reduce the blastholes number, for approximately the same amount of fragmented volume. On the other hand, each cartridge of Emulex 5 (C_{em5}) has a price slightly higher than the one of the column charge Emulex 1 (C_{em1}), but lower with respect to the one of the booster Emulex 2 (C_{em2}):

$$C_{em1} < C_{em5} < C_{em2} \tag{8}$$

In this way, it is possible to reduce the blastholes number without significant increasing of the explosive's costs.

Regarding the blasting schemes, the following four scenarios (Table 5) were tested for optimization, with respect to the current one (0).

Three indexes were used to evaluate the quality of the optimization, by respecting the constraints. The time saving index is related to the time necessary for exploiting 1 ton of material, the cost saving index is related to the cost of 1 ton of blasted material, and the safety upgrade index is related to the percentage of retained material having dimensions over 1000 mm, since larger blocks pose the operators at risk. The higher index value, it means the worse results of blasting. The three indexes are presented in Table 6.

Since the three indexes have different units, a quality matrix was introduced, assigning the following scores (Table 7). They were hypothesized based on lags provided by the experience of the mine operators, and hence subjectivity affected by human limitations.

3 Results

3.1 Alternative Scenarios

Excluding the Business as Usual (BAU) scenario, a total of nineteen possible variation scenarios were tested (4 charging alternatives×5 blasting schemes—BAU). For each of them, the result in terms of fragmentation curve was compared with the BAU (Fig. 6). Moreover, a ranking of the optimization scenario was made by comparing the results of the indexes in Tables 6 and 7. The nineteen possible scenarios compared to BAU are (Table 8):

Table 9 Comparison of results for the three indexes between the Business as Usual scenario and the four proposed optimizations

Scenario	Time saving index TSI (h / t)	Cost saving index CSI (€ / t)	Safety upgrade index SUI (% / t)
Business as usual scenario	0.0069	1.57	24
Optimized scenario O_1 Use of Emulex 5 9 cartridges for blastholes 3.0 m stemming Burden 3.10 m Spacing 4.50 m	0.0062	1.49	11
Optimized scenario O_2 Use of Emulex 5 9 cartridges for blastholes 3.0 m stemming Burden 3.00 m Spacing 4.60 m	0.0060	1.49	10
Optimized scenario O_3 Use of Emulex 5 9 cartridges for blastholes 3.0 m stemming Burden 3.10 m Spacing 5.00 m	0.0061	1.43	13
Optimized scenario O_4 Use of Emulex 5 9 cartridges for blastholes 3.0 m stemming Burden 3.00 m Spacing 5.10 m	0.0061	1.43	12
% Diff. BAU-O_1	10.14%	5.10%	54.17%
% Diff. BAU-O_2	13.04%	5.10%	58.33%
% Diff. BAU-O_3	11.59%	8.92%	45.83%
% Diff. BAU-O_4	11.59%	8.92%	50.00%

Table 10 Best results among the various optimizations, for each index independent from each other

Index	Best optimization scenario	Value	Result
Time saving index TSI (h / t)	O_2	0.0060	Saving of 154 working hours per year
Cost saving index CSI (€ / t)	O_3 / O_4	1.43	Saving of 24,150 € of costs per year
Safety upgrade index SUI (% / t)	O_2	10	Reduction of 14% of blocks of dimension higher than 1 m per year

Table 11 Comparison of total scores between the business as usual and the four optimization scenarios

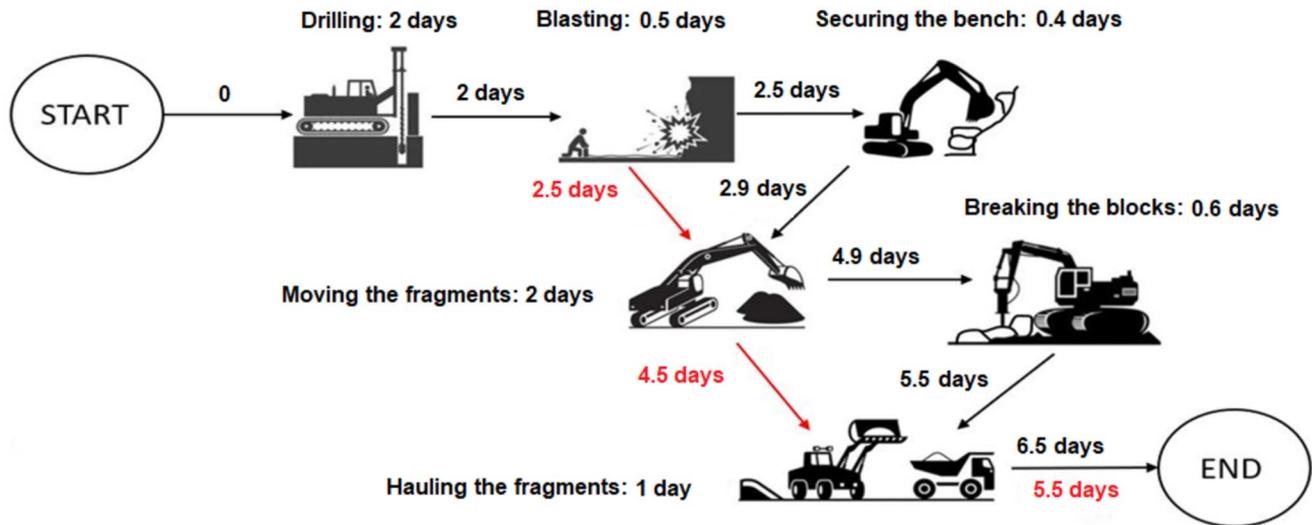| Scenario	TSI score	CSI score	SUI score	Total score
Business as usual scenario	-	-	-	-
Optimized scenario O_1	+7	+8	+13	+28
Optimized scenario O_2	+9	+8	+14	+31
Optimized scenario O_3	+8	+14	+11	+33
Optimized scenario O_4	+8	+14	+12	+34

3.2 Cost, Time, and Safety Improvements Expected for the Optimization Scenarios

All the alternative scenarios were compared together and with the BAU scenario, by using the three indexes. At last, four alternative scenarios were considered the optimized scenarios. They are presented in Table 9, together with their indexes.

Table 10 indicates the best optimization scenario for each of the indexes, considering each index independent. This comparison is made on annual basis, according to the authorized volumes of excavation.

Table 12 Best results among the various optimization, considering the indexes interconnected

Best optimization scenario: O_4		
Index	Value	Result
Time saving index TSI (h / t)	0.0061	Saving of 145 working hours per year
Cost saving index CSI (€ / t)	1.43	Saving of 24,150 € of costs per year
Safety upgrade index SUI (% / t)	12	Reduction of 12% of blocks of dimension higher than 1 m per year

Fig. 7 Prospected modified process of the Monte Tondo gypsum quarry, due to the blasting optimization results

Of course, the three indexes are interconnected in fact, and it is not possible to choose a solution for saving time and another solution for reducing the costs. However, the three indexes cannot be summed; therefore, in order to find the best optimization among the four proposed scenarios, it was necessary to use the assignment scores from Table 7. With respect to them, the results are as follows (Table 11):

Hence, the final results for the optimized scenario O_4, getting the maximum scores, are in Table 12.

The optimized scenario O_4 provides a theoretical variation of the quarry process. Based on working days, the prospected modified process for the gypsum quarry is shown in Fig. 7.

In total, around half a day is expected to be saved for each blast, thanks to the proposed optimization factors. The result approaches the best path, and at the end one day is reduced in the operational activities of the mine.

4 Discussion

The obtained results are inevitably influenced by the geological uncertainty of the gypsum body, which affects the rock parameters and then the rock factor used in the Kuz-Ram model. Due to this, a sensitivity analysis has been conducted in order to understand how an error on the rock parameters measurement and estimation could affect the model result. The simulation of the blasting on the software O-Pitsurface® has been repeated many times, using the different rock factors. Then, based on that, it was possible to simulate the alternative results of the fragmented materials dimensions. The results are visualized in Figs. 8 and 9 considering the two identified limits affecting gypsum exploitation: the retained material higher than 1000 mm and the one higher than 600 mm.

As expected, an increase of rock factor causes an increase of retained material, due to less effect of used explosives. However, it is worth noticing that the increase of retained materials over 1000 mm is much higher, in percentage variation, than the one over 600 mm. In both cases, the selection of the optimization scenario causes a higher variation in sensitivity analysis with respect to the BAU scenario. With the proposed optimization scenario then, an error in the definition of the rock factor provokes notable variations in blasting results, while the current scenario gives more margins for errors. This aspect must be carefully considered in the next decisional steps for the prosecution of the gypsum exploitation.

Fig. 8 The sensitivity analysis of results variation for retained material over 1000 mm dimension, based on rock factor natural variability with respect to the lab measurements

Fig. 9 The sensitivity analysis of results variation for retained material over 600 mm dimension, based on rock factor natural variability with respect to the lab measurements

5 Conclusions

The aim of the work was to optimize the efficiency of the blasting carried out in the Monte Tondo quarry for the extraction of gypsum, evaluating three fundamental aspects:

1. The reduction of blast costs for the same volume of fragmented materials
2. The reduction of exploitation time for the same volume of removed rocks
3. The improvement of safety conditions during the handling of blasted materials

To achieve the aforementioned objectives, the O-Pitsurface® design and simulation software for blasting in quarries and open pit mines was used. By comparing various optimization scenarios, it was possible to reach a potentially optimum one, providing.

1. A time saving of approximately 145 h/year of work related to drilling and blasting phases
2. An economic saving of approximately €24,150/year, derived from the reduction of blastholes numbers
3. An improvement in safety conditions of 12%, determined by a dimension reduction of the fragmented materials, easier to handle safely

Focusing only on one of the three aspects, the optimizations can even be higher. Therefore, a matrix of potential variants was realized, in order to provide to the quarry director a range of possibilities. During the design phase of the blasts, the director would therefore be able to choose which optimization variant to implement, depending on the desired aspect (cost reduction, time reduction, improvement of safety conditions). Next steps of the work are to validate the hypothesis by carrying out in situ tests according to the envisaged variants, based on the optimization scenarios. The final target will be to realize a general workflow to be applied on various types of gypsum quarries, so to improve the blasting performances of the whole sector.

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Declarations

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