BLASTING FRAGMENTATION MANAGEMENT USING COMPLEXITY ANALYSIS

J. Seccatore
Landscape, Environment and Geotechnologies Engineering Department, Polytechnic of Torino, Italy
jacopo.seccatore@gmail.com

G. De Tomi, M. Dompieri
Mining & Petroleum Engineering Department, Polytechnic School, University of São Paulo, Brazil

A. Rezende
Sociedade Extrativa Dolomia Ltda – Taubaté, Brazil

RESUMO
ESTE DOCUMENTO APRESENTA UM PROJETO DE PESQUISA QUE BUSCA APRIMORAR AS CONDIÇÕES DE PREVISIBILIDADE DO DESMONTE PARA AUMENTAR A EFICIÊNCIA DA BRITAGEM PRIMÁRIA. O OBJETIVO PRINCIPAL É O DESENVOLVIMENTO DE MÉTODOS PARA ENCONTRAR UMA SOLUÇÃO ROBUSTA PARA A PREVISIBILIDADE DA FRAGMENTAÇÃO DO DESMONTE E PARA PLANEJAR O DESMONTE COM O PROPÓSITO DE ALCANÇAR AS METAS DE PRODUTIVIDADE DA BRITAGEM. O TRABALHO UTILIZA FERRAMENTAS DE ANÁLISE DE COMPLEXIDADE INTRODUCINDO UMA ABORDAGEM PARTICULAR DE SISTEMAS COMPLEXOS, INÉDITA EM MINERAÇÃO E APLICAÇÕES DE DESMONTE

PALAVRAS-CHAVE: perfuração e desmonte; fragmentação; análise de complexidade

ABSTRACT
THIS PAPER DESCRIBES A RESEARCH PROJECT WHICH AIMS TO INCREASE THE EFFICIENCY OF PRIMARY CRUSHING THROUGH BLASTING PERFORMANCE ANALYSIS AND FORECASTING. THE MAIN OBJECTIVE IS THE DEVELOPMENT OF METHODS FOR DEVISING A ROBUST SOLUTION TO PREDICT BLASTING FRAGMENTATION AND FOR DESIGNING THE BLAST WITH THE PURPOSE OF ACHIEVING THE CRUSHER PRODUCTIVITY TARGETS. THE RESEARCH APPLIES COMPLEXITY ANALYSIS TOOLS TO INTRODUCE A PARTICULAR APPROACH TO COMPLEX SYSTEMS THAT HAS NEVER BEEN USED BEFORE IN MINING AND BLASTING APPLICATIONS.

KEYWORDS: drilling and blasting; fragmentation; complexity analysis;
INTRODUCTION

Rock fragmentation due to blasting operations is the key result of aggregates and ore mining activity before plant treatment. It has been observed in many case studies (e.g. Sastry & Chandar 2004, Ryu et al. 2009, Clerici & Mancini et al. 1974) that power consumption of loading machineries and crushers operating on the site and of primary crusher operating on the plant depends on the ratio of desired fragmentation obtained from the blast. On the other side, a lower ratio of fragmentation decreases the primary blasting costs (Ryu et al.).


- increased secondary blasting
- increased rate of muck shovel loading
- increased difficulty in transport
- increased energy consumption at crushing or milling
- low crusher or mill performances

On the other hand, when operating on fragmentation results in order to reduce secondary blast or other kind of secondary fragmentation before crushing, primary blast costs and drilling costs increase (Ryu et al. 2009), making the efficiency of the mine site workings decrease.

When secondary blasting is avoided or reduced to its minimum in order to increase mine site working efficiency, the amount of cost related to the reduction of dimension of blocks is transferred to crushing or milling, reducing its efficiency and increasing its costs.

McKenzie’s study (1967) is nowadays a classical analysis that showed how loading, hauling and crushing costs decreased with increasing rock fragmentation while drilling and blasting costs increased with increasing rock fragmentation.

The requirement of both efficiency and cost has to be properly managed. This research intends to analyse mining operations and plant crushing and find an appropriate way to obtain a high constancy in blast fragmentation results under highly variable environment, improving the
robustness of blast fragmentation models and to set a robust method to design the blast in order to grant the productivity of the crushing/milling process.

The present paper is the first stage of this ongoing research.

**VARIABLES**

A blast in open pit mining has several variables that can contribute to its results in terms of fragmentation. These variables can be classified in terms of geometry of bench and drilling, explosive charge, initiation system and rock qualities. Many authors (e.g. Lu & Latham 1998, Thornton et al. 2002, Mancini & Cardu 2001, Chakraborty et al. 2004) agree with a similar classification.

<table>
<thead>
<tr>
<th>VARIABLES</th>
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<tbody>
<tr>
<td><strong>GEOMETRY</strong></td>
<td><strong>EXPLOSIVE CHARGE</strong></td>
</tr>
<tr>
<td>Drilling diameter</td>
<td>Explosive type(s)</td>
</tr>
<tr>
<td>Number of holes</td>
<td>Explosive(s) density</td>
</tr>
<tr>
<td>Number of rows</td>
<td>Bottom Charge</td>
</tr>
<tr>
<td>Bench Height</td>
<td>Column Charge</td>
</tr>
<tr>
<td>Burden</td>
<td>Specific Charge</td>
</tr>
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<td>Spacing</td>
<td>Coupling ratio</td>
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<td>Hole length</td>
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<td>Underdrilling</td>
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<td>Stemming</td>
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<tr>
<td>Inclination</td>
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</tbody>
</table>

Table 1 – Variables of the blast

Fragmentation is a “process of transition from in-situ to blasted block size resulting from the application of explosive energy” (Lu & Latham, 1998). Many case studies (e.g. Grenon et al., 1998, Lu & Latham, 1998, Chakraborty et al. 2004) focused on the predictability of blasted block sizes depending on the natural sizes of the blocks in the rock mass due to the structure of natural joints, discontinuities and fractures.

The action of fragmentation of the explosive energy on the rock has been widely recognized (e.g. Berta 1985, Moser 2008) as related to the specific energy [MJ/m$^3$] of the blast and to the specific surface [m$^2$/m$^3$] of the obtained fragmented rock.

Many other studies (e.g. Clerici & Mancini 1974, Moser 2008) have also shown that the results of fragmentation are largely dependent on the specific charge of explosive [kg/m$^3$].

The coupling ratio $\varnothing_{\text{hole}} / \varnothing_{\text{cartridge}}$ is also a representative parameter of the effect of the charge over the obtained fragments (e.g. Berta 1985, Mancini & Cardu 2001).
The interdependencies between all these variables will be analyzed through Complexity Analysis tools, a particular approach to complex systems that has never been used before in mining and blasting applications.

**COMPLEXITY ANALYSIS**

Complexity is a function of the structure and the entropy of any system. The difficulty in managing a system derives from the complexity of its structure and from the uncertainty about the data it uses. Complexity derives from the design; uncertainties derive from the realization and the work environment. The need is to manage complexity through design and manufacturing.

Complexity is the property of a system of possessing ability to surprise through unexpected events. The degree of robustness of the system is proportional to the margin between the actual level of complexity $C$ and the critical level of complexity $C_{CR}$.

![Figure 2 - Complexity levels of a system](image)

This margin is known as *topological robustness* (Marczyk, 2008) and quantifies the system’s ability to preserve its functionality under varying conditions.

The principle of complexity derives from the Principle of Incompatibility (Zadeh, 1973): “High precision is incompatible with high complexity”. Hence, as stated by the Principle of Complexity (Marczik, 2008) “when the complexity and uncertainty of an engineering system increases, our ability to predict its behavior diminishes until a threshold is reached beyond which accuracy and significance become almost mutually exclusive”.

The risk exposure of any dynamical system can be measured and understood in an innovative way via complexity, through Ontonix software OntoSpace™.

In order to perform an analysis of the complexity of a system, OntoSpace™ analyses multi-dimensional maps images that report the raw measured data plotting $x_i$ Vs $x_j \forall x_{i,j}$ ∈ variables of the system, with $i \neq j$. Each map is divided into cells. On each cell an image analysis is performed. Through this image analysis technology, multi-dimensional data are transformed into Process Maps. This is done for each couple of variables of the system. If a structure appears between $x_i$ and $x_j$, a link is created between the two variables. The result of a process map is a graph of nodes (variables) and arcs (interconnections).
The level of complexity is derived from the distribution of connections between the variables: the more dispersed is the cloud of connection dots on multidimensional maps, the higher is the level of complexity between the two variables. This appears on the System Process map in red dots (low dispersion) and blue dots (high dispersion). The degree of complexity is reported on the arcs.

The results given by OntoSpace of this analysis performed over data are:
- the measurements of the levels of complexity
- a summarized overview of input data and analyzed relationships
- the degree of robustness of the system
- a graph showing the level of complexity of the system and its critical level

Furthermore:
- the degree of interconnection of two variables is represented on the arc connecting them
- separate graphs represent the contribution of each variable to total complexity

The reliability (credibility) of a model is the percentage of fitting of its results with reality or test results. Both the model and reality are systems, with a large amount of data, characterized by a degree of complexity. Hence, a Complexity Analysis can be performed over the model and the test data in order to measure their degrees of complexity. The reliability of a model can be considered as the percentage of fitting between the complexity of the model and the complexity of the system.

A measurement of the reliability (credibility) of a model can be given by the Model Credibility Index (Marczyk, 2008).

\[ MCI = \frac{|C_{test} - C_{model}|}{C_{test}} \]

- if \( C_{test} > C_{model} \) the Model (generally) misses physics
- if \( C_{test} < C_{model} \) the Model (generally) generates noise

This complexity analysis will be carried on the models, on the field data, and between the two. The results will lead to:
- a complexity management of blast fragmentation models
- an understanding of the complexity of the blast fragmentation process and its parameters
· a management of the robustness of the models to grant the best predictability under highly variable conditions

COMPLEXITY ANALYSIS APPLICATION

For this stage of the research the data have been taken from the mine direction of Dolomia Extractive Company in Taubaté SP – Brazil.
In this preliminary stage Complexity Analysis has not yet been applied to the modelling of fragmentation. In order to test C.A. the first approach has been the determination of the levels of complexity in the dimensioning of the geometrical and charging parameters of the blast.
To achieve this analysis three stages have been analyzed:
· The empirical dimensioning model used by the mine direction
· An analytical dimensioning model proposed by Berta (1985)
· The field data of drilling pattern and charging used in the mine during blasting operations in the month of March 2010

Mine Direction Model (empirical)

The model used by the mine direction to dimension the blast is based on an empirical proceeding.
It refers to the monomial formula:

\[ Q = PF \cdot H \cdot E \cdot V \]

Where:
- \( Q \) Quantity of explosive per hole [kg]
- P.F. Powder Factor, or specific charge [kg/m³]
- H Height of the bench [m]
- E Spacing between the holes [m]
- V Burden [m]

All the geometrical variables of the blast are correlated by empirical thumb rules, beginning from the available drilling diameter:

\[ V = 33 \div 39 \phi_f \]
\[ E = 1,15 \div 1,30 V \]
\[ B = 0.7 V \]
\[ U = 0.3 V \]

Where B [m] is the stemming of the hole and U [m] the underdrilling.
The specific charge is empirically determined. The mine direction refers it to the mass of the rock instead of its volume [g/t], and considers two different conditions of Massive Rock and Weathered Rock:

\[ P.F. = 150 \div 200 \frac{g}{t} (massive \, rock) \]
\[ P.F. = 80 \div 100 \frac{g}{t} (weathered \, rock) \]
The charge of explosive per hole is consequently calculated knowing the volume weight of the rock \( \rho_R \) [t/m\(^3\)]:

\[
Q = P \cdot F \cdot H \cdot E \cdot V \cdot \rho_R
\]

**Berta’s Model (analytical)**

Berta (1985) wrote a blast design model based on a total energetic balance of the blast. According to Berta, the expression of the specific charge can be written as follows:

\[
P \cdot F = \frac{s \cdot \varepsilon_{ss}}{\eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \varepsilon}
\]

Where:

- \( s \) - desired degree of fragmentation [m\(^2\)/m\(^3\)]
- \( \varepsilon_{ss} \) - rock specific surface energy [MJ/m\(^2\)]
- \( \varepsilon \) - explosive specific energy [MJ/kg]
- \( \eta_1 \) - acoustic transfer efficiency
- \( \eta_2 \) - coupling efficiency
- \( \eta_3 \) - energetic fragmentation transfer efficiency

The desired degree of fragmentation takes into account the maximum desired diameter of the fragments in the muckpile:

\[
s = \frac{64}{D_M}
\]

Where the value 64 is an empirical constant.

The specific surface energy is a proper energetic characteristic of the rock, referred to the energy necessary to break it into fragments, and can be either determined experimentally, or derived from literature. The acoustic transfer efficiency takes into account the acoustic impedance of the rock \( I_r \) and of the explosive \( I_e \):

\[
\eta_1 = 1 - \frac{(I_e - I_r)^2}{(I_e + I_r)^2}
\]

The coupling efficiency takes into account the coupling ratio \( \phi_{hole}/\phi_{cartridge} \) considering the backlash between the hole wall and the cartridge:

\[
\eta_2 = \frac{1}{e^{\phi_{h}/\phi_c} - (e - 1)}
\]

The energetic fragmentation transfer efficiency is always considered as \( \eta_3 = 0.15 \) as Berta analytically demonstrates that the amount of energy transferred to the rock to produce
fragmentation is 15% of the total. The burden can then be calculated after the diameter of the cartridge \( \Phi_c \), the specific charge and the density of the explosive \( \rho_e \):

\[
V = \phi_c \sqrt{\frac{\rho_e \pi}{4P.F}}.
\]

Berta usually suggests a squared drilling pattern, hence considering \( E = V \)

Known the height of the bench \( H \), the charge per hole \( Q[kg] \) is therefore calculated using again the monomial formula:

\[
Q = PF \cdot H \cdot E \cdot V
\]

**Mine In-Situ Data**

In Taubaté mine, Dolomia Company extracts dolomitic limestone by open pit blasting of horizontal benches with sub-vertical holes. Depending on the zone of the quarry, the rock appears to be from compact to quite weathered. The data used in this analysis are taken from the field reports compiled by the blasters and referring to the drilling pattern and charging parameters used on the field.

<table>
<thead>
<tr>
<th>Burden of rows</th>
<th>n# of rows</th>
<th>Bench Length [m]</th>
<th>Num. of holes [-]</th>
<th>Bench Height [m]</th>
<th>Bench Volume [m3]</th>
<th>Bench Weight [t]</th>
<th>Explosive Type</th>
<th>Coupling Ratio</th>
<th>Qesp. l (tot) [g/t]</th>
<th>P.F. (tot) [kg]</th>
<th>Qesp. l (hole) [kg]</th>
<th>Volum. of single mine [m3]</th>
<th>P.F. (single mine) [kg/m3]</th>
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<tr>
<td>3.6</td>
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<td>25</td>
<td>6.7</td>
<td>601</td>
<td>1563</td>
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<td>172</td>
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<td>2</td>
<td>16</td>
<td>12</td>
<td>7.5</td>
<td>480</td>
<td>1248</td>
<td>Valex</td>
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<td>1.25</td>
<td>150</td>
<td>120</td>
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<td>Valex</td>
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<td>1.25</td>
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<td>20</td>
<td>11</td>
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<td>1872</td>
<td>Valex</td>
<td>2x24</td>
<td>1.25</td>
<td>400</td>
<td>214</td>
<td>22</td>
<td>40</td>
</tr>
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<td>1</td>
<td>18</td>
<td>9</td>
<td>7.5</td>
<td>270</td>
<td>702</td>
<td>Valex</td>
<td>2x24</td>
<td>1.25</td>
<td>125</td>
<td>178</td>
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<td>14</td>
<td>10</td>
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<td>2x24</td>
<td>1.25</td>
<td>350</td>
<td>120</td>
<td>25</td>
<td>80</td>
</tr>
</tbody>
</table>
An observation on these data not related to complexity is that the volume of competence of a single mine increases when the total volume of the bench increases, and the P.F. decreases when the total volume of the bench decreases. This can be due to the usual blasting of larger benches in weaker rock, where the necessary P.F. is lower.

**Complexity Analysis of the Mine Direction Model**

Complexity Analysis performed on this model leaded to the following results:

![System process map and scatter plot of P.F. of the empirical model](image)

The model shows such a high degree of empiricism that at this stage no correlations appear between the geometrical characteristics of the pattern and the charging parameters. This means that, according to complexity, this kind of modelling cannot be based on theoretical proceedings without calibrating the specific charge with tests.

The P.F. is mainly determined by the weathering condition of rock, being calculated around two central values for massive or weathered rock. That creates two attractors, as shown in Figure 4 (right side), which cannot be explained anywhere else in the model. The addition of an intermediate variable in the process to represent the weathering condition of rock could create the missing link between the geometrical characteristics block to the rest of the system, leading to a more realistic complexity computation.

**Table 3 – Contribution to Complexity of empirical model’s parameters**

<table>
<thead>
<tr>
<th>Level of contribution to Complexity</th>
<th>Parameter</th>
<th>Percentage of contribution to complexity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>Stemming</td>
<td>25.03</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>Burden</td>
<td>25.01</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>Underdrilling</td>
<td>24.81</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>Spacing</td>
<td>24.77</td>
</tr>
</tbody>
</table>
The aspect of the Complexity Profile is totally dominated by these four parameters:

Since the drilling parameters have no connection with the others, they can be deleted to consider a simplified datasheet that takes into account only the height of the bench and the P.F. (as input) and the charge per hole as a result. The results are shown in the following figure, reported in Table 7 and commented below it.

In this case the complexity of the system drops to a value very close to the one of the real field data, as shown in the paragraphs below. In this simplified datasheet, complexity correlations appear only between the specific charge and the charge per hole. The height of the bench doesn’t appear to influence the complexity of the model: it depends only on the correlations between the kind of rock encountered (from which the specific charge depends) and the charge per hole.

It can be concluded that, in this kind of empirical blasting modelling:
- it is necessary to calibrate the P.F. with test blast at the beginning of excavations
- the workings that mostly influences the complexity of this design model are the drilling and the stemming
- the robustness is artificially high, due to the hard coded analytical geometric relationships of the model that add structure to the system and increases global entropy due to additional information exchange.
- in this kind of modelling the height of the bench doesn’t influence the complexity of the determination of the result (charge per hole)

### Complexity Analysis of Berta’s Model

Berta’s model contains many more variables than available at this stage of the analysis. Missing values of geo-morphological variables have been taken from literature suggested by Berta himself simulating the conditions of the dolomitic limestone. The energetic and acoustic values of the explosive, where not available, have been assumed as the same with similar emulsion explosives. The choice of values, anyhow, doesn’t affect the behaviour of the model. Complexity Analysis performed on this model leaded to the following results:

![System process map and Complexity profile of the analytical model](image)

The variables appear in a high degree of inter-correlation. This analytical formulation is not only more complicated than the empirical approach, but has also a higher degree of complexity. Complexity is, mathematically, an index of the structure of the system, hence this model seems to be more consistent in structure. This is due to the increased functionality of the model that takes into consideration many additional parameters. Complexity appears higher because of the greater number of active nodes, links and rules detected by system maps. Connections appear redundant, and this contributes to increase complexity. On the other side, its level of complexity is very close to its critical level, hence it appears very fragile. The model generates a lot of noise and has a low level of confidence. This means that the model might be able to generate fuzzy results if fed with a high number of highly varying inputs.
The five parameters with the highest level of contribution to the total complexity of the model are:

Table 4 - Contribution to Complexity of analytical model’s parameters

<table>
<thead>
<tr>
<th>Level of contribution to Complexity</th>
<th>Parameter</th>
<th>Percentage of contribution to complexity [%]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Burden</td>
<td>16.95</td>
</tr>
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<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>Mine Volume</td>
<td>16.83</td>
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<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>Rock Density</td>
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<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>Explosive Specific Energy</td>
<td>11.07</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt;</td>
<td>Specific Charge</td>
<td>9.26</td>
</tr>
</tbody>
</table>

As shown in Figure 7, The shape of the complexity profile appears to be well distributed, very similar to the shape of natural data.

It can be concluded that, in this kind of analytical blasting modelling:
- the system appears fragile, close to its critical level of complexity
- the variables appear strongly inter-correlated and their inter-connections redundant
- the complexity profile models quite well the complexity profile of a real system
- the higher functionality, and hence complexity, of the model can account for a better representation of the phenomena involved

Complexity Analysis on Mine In-Situ Data

Complexity Analysis performed on this data leaded to the following results:

Figure 8 – System process map and Complexity profile of field data

The symbols appearing are:
The complexity of this amount of data appears considerably low, and very far from its level of criticality.

The parameters that mostly contribute to the total level of complexity of the system are:

As shown in Figure 8, the complexity profile of the system is totally dominated by these parameters:
- the large dimension of the bench to be blasted (number of rows x total length of the blast) largely contribute to the complexity of the operations
- the number of rows influences the charging parameters, confirming what is suggested by many authors (e.g. Mancini & Cardu, 2001) to vary the P.F. for the holes of the rows after the first one
- the degree of complexity of this kind of working appears to be very low and far away from its criticality

**Comparison of the models**

This resume has been done to compare the complexity of these two extremely different approaches to blast design.

It clearly appears at this stage that the analytical approach, with a greater number of active nodes, links and rules, appears more affected by complexity. Also its parameter that mostly contributes
to complexity appears to be much more critical for the system than the one in the empirical model.

**Comparison model Vs in-situ data**

This resume compares the model used by the Mine Direction to dimension the blasts with the real data applied for drilling and charging.

<table>
<thead>
<tr>
<th>Complexity Parameters</th>
<th>Dolomia Model</th>
<th>Dolomia In-Situ Data</th>
<th>Dolomia Model simplified datasheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complexity Level C</td>
<td>6.39</td>
<td>1.98</td>
<td>2.12</td>
</tr>
<tr>
<td>Critical Complexity C&lt;sub&gt;CR&lt;/sub&gt;</td>
<td>8.16</td>
<td>2.89</td>
<td>2.56</td>
</tr>
<tr>
<td>Robustness</td>
<td>73.9</td>
<td>86.8</td>
<td>70.3</td>
</tr>
<tr>
<td>Model Credibility Index</td>
<td></td>
<td>M.C.I. = 2.22</td>
<td>M.C.I. = 0.07</td>
</tr>
</tbody>
</table>

It appears that the complexity of the whole model is much higher than the complexity of the field data. This is due to its high dependency on the geometrical correlation of the drilling pattern. On the other hand, simplifying the datasheet to its essential variables (height of the bench and pre-determined P.F.), that possess a degree of inter-correlation with the charge per hole as a result, the degree of complexity appears very close to the one of the field data. It can be concluded that in the workings executed in Dolomia mine, under the point of view of Complexity, the drilling and the charging are separated and independent characteristics of the blast. In any case, looking at the System Map of the model and of the real data, it is clearly visible that the model totally misses some links between geometrical and charging parameters that are visible in the Map of real data. This confirms that this kind of empirical model needs calibration. In both cases the model depends largely on the determination of P.F. that leads the inter-connections with the charge per hole over all the other variables. This increases the complexity of the model. Until testing is accomplished, this kind of empirical model generally generates noise that needs calibration to be eliminated.

**CONCLUSIONS**

As mentioned above, blasting techniques have never been analyzed under the point of view of their complexity. Hence, none of the comments reported above can have a general meaning at this stage. In future analysis, the models should be built using more abundant and consistent field data. The Complexity Analysis performed in this paper has been carried out with the objective of outlining the potential benefits of applying this technique to blasting applications. The general conclusions about the results obtained are:

- Complexity Analysis allows a clear understanding of the correlations between the variables in blasting systems;
- Complexity Analysis is not meant to be used on purely empirical models;
- Robustness and complexity levels of models and real data can be used to compare different models and between model and to evaluate field data;
- Complexity Analysis allows the understanding of the behaviour of critical variables that can generate instability in the system thus leading to unexpected results.
The approach to this problem, searching for the optimum, appears to be inefficient. The geological environment is characterized by too many uncertainties to have an optimum valid for many applications. Researching for robustness in blast design results in much more efficiency. Robustness is the capability of the system to produce expected and acceptable results under varying or even unforeseen conditions. Since the geology varies from site to site, and often from bench to bench on each site, setting a robust method can grant better overall results in varying environments, lowering the costs and increasing benefits such as predictability and safety.

The continuation of this research project is expected to produce results related to:
- Identification of the most critical parameters in blasting operations through complexity analysis of the blast fragmentation process
- Selection of the most robust model that can grant a more controlled variability in the results, even at the cost of greater precision, under variable operative conditions through topological robustness management

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