ALGORITHM DEVELOPMENT AND IMPLEMENTATION FOR GEOREFERENCED PARTICLE SIZE DISTRIBUTION (PSD) DATA

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ABSTRACT

Any organization that subjects its activities to a continuous improvement process must be able to adequately measure the results of the implemented changes in order to pursue better results over time. This is no different for mining companies. When it comes to blasting, an accurate fragmentation analysis can correlate blast design and rock mass parameters to particle size distribution, enabling us to further analyze the correspondence of specific design patterns, applied to specific rock mass properties and the result in measured fragmentation indicators, such as P80 and fines percentage.

Over time, various tools were developed that enabled us to obtain such fragmentation analysis, albeit each of them had their own shortcomings. The first ones involved taking photos of the muck pile including a scale object, such as a ruler or a basketball, uploading those photos to a PC and using specialized software to analyze the PSD of each one. As a result, the analysts would get a PSD curve that served as a reference point for the performance of the blast. This method, which is still used, has major shortcomings. The most obvious one is that it is only able to capture a slice of the blast, which corresponds to the exposed section of the muck pile the analyst has access to, and even there its reach is limited to the areas that are safe for getting close enough for placing the scale, which are not many. Consequently, this is a very limited way to get a fragmentation performance assessment for a blast.

Currently, many autonomous systems capable of taking continuous pictures of the muck pile are available in the market. Installed on a shovel, these systems can take a continuous stream of pictures that are later analyzed automatically without the need for human intervention. These systems greatly increase the volume of data and, consequently, we have a PSD curve that is more representative of the blast performance. However, there is still one piece of the equation missing: an exact location of the samples taken.

To address this issue, a software solution was developed for the FRAGTrack™ system owned by Orica. This system uses a fixed camera to take continuous photos of the muck pile and then analyzes them for PSD data. Using high precision GPS data from two antennas installed in a shovel, which is obtained from a live feed from the Fleet Management System (FMS), it is possible to determine its exact position and heading in the local mine coordinate system. From here, and knowing the distance of the FRAGTrack™ camera to the muck pile, the developed algorithm can calculate the coordinates of the section of the muck pile imaged by the camera. Tests have shown that, PSD data from the system can be

associated with coordinates for each sample with an accuracy of ±1 meter in X, Y and Z.

From this implementation, it is possible to produce georeferenced PSD data with a precision that allows to correlate the results to a single borehole in a blasting project. This breakthrough allows to view the corresponding fragmentation for each borehole and build dashboards or even large-scale maps that show the PSD results for an area of the pit. Consequently, we can now understand the results of fragmentation related to specific rock mass characteristics and explosive energy used to precisely predict the outcome of subsequent blasting on a borehole-by-borehole basis, thereby enabling a much better assessment of the blasting results and improving them on each subsequent blast.

1. Introduction

Blasting is the first step in the process of comminution, as it allows the breakage of the intact rock mass in fragments that are later processed to reduce their size further in order to enable mineral recovery.

The importance of continuously improving blasting results cannot be understated, as it frequently brings significant processing cost reductions or increased plant throughput. These benefits greatly compensate for any additional effort or cost incurred when improving the blasting process.

Acquiring and reviewing data to determine if the changes made to any process are effective in providing the desired results is a critical step. When it comes to blasting, current available technologies are limited in their application since there isn’t a solution that combines the representability given by autonomous systems with the precise location of the samples taken for analysis. Hence, a new technology must be developed for the georeferencing of Particle Size Distribution (PSD) analysis, in order to accurately correlate fragmentation results to the contributing factors present in each blast.

The main objective of this study is to demonstrate the viability of georeferencing fragmentation analysis data, with high accuracy, through the development of a specialized algorithm.

2. The relevance of analyzing blasting results

In order to understand why is it important to properly assess and review our blasting results, the impact of analyzing the results in any given process must first be understood.

2.1. The Continuous Improvement approach

Continuous Improvement, as defined by the American Society of Quality, is the ongoing improvement of products, services or processes through incremental and breakthrough improvements. Incremental improvements are viewed as the results achieved over time and breakthrough improvements as the results achieved all at once. This approach is followed by a growing number of companies across various industries, aiming to increase the value of their products and services following a methodology aligned with this philosophy. The expected outcomes include streamlined workflows and project costs reduction.

One of the most widely used tools for Continuous Improvement, is a four-step quality assurance method known as the PDCA cycle, which name is an acronym from the stages it comprises:

- Plan: at this stage, an opportunity for improvement is identified and corresponding changes designed and reviewed for their implementation.
- Do: the changes are implemented on a small scale that allows them to be properly measured and controlled.

- Check: collected data is used to analyze the impact of the changes made and determine if they produced the desired outcomes.
- Act: the successful changes are implemented in a wider scale and their results are continuously assessed. If the changes were not successful, the cycle begins anew.

As changes are implemented on a wider scale, their results are continued to be reviewed and new areas for improvement are identified, which allow organizations to enter a Continuous Improvement cycle.

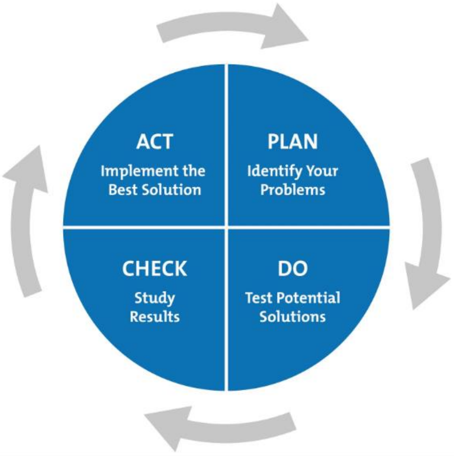

Figure 1: PDCA cycle model. Source: The W. Edwards Deming Institute®

Checking and analyzing the impact of the changes designed for improving processes is a critical stage of a Continuous Improvement cycle. If the ability to properly measure the outcomes of designed variations is not available, it would be impossible to conclude whether those variations are effective or not. In consequence, implementing them at a wider stage could critically damage the associated processes incurring in increased costs, over complex processes and other negative outcomes, the very opposite results that are intended.

2.2. Continuous improvement on blasting

When approaching the blasting process in an open pit mine with a Continuous improvement mindset, it becomes clear that the results of said blasting must be properly measured and analyzed in order to be able to follow the PDCA methodology correctly. The benefits of adopting such methodology in this process include:

- Adequate delivery of explosive energy to reduce costs of explosives and blasting services
- Expand blast patterns to reduce drilling costs
- Better adjustment of fragmentation results to processing plant needs

Since blasting is the first step in the comminution process, fragmentation is an adequate measure of the outcome of a blast. Many open pit mines have set thresholds for fragmentation results, such as a minimum percentage of rock particles below 1 inch required, or a maximum rock fragment size. These thresholds align with the processing plant feed requirements, which in turn are aligned with minimizing energy consumption while maximizing throughput. For these reasons, the particle size distribution (PSD) of the rock mass blasted and turned into muck pile is a very good indicator for the performance of this process.

3. Available technologies for fragmentation analysis

Having established the need for adequate fragmentation analysis in order to properly assess blasting results, and use them as an indicator for a continuous improvement process, an effective method of carrying out said analysis must then be implemented.

There is a vast array of methods and technologies available to miners today for measuring fragmentation, but for the purpose of this study, we will classify them in two broad categories: manual analysis and automated analysis. This section is not intended as a comprehensive list of the current available technologies, but as a general reference of the main features, pros and cons of the two fragmentation analysis categories proposed.

3.1. Manual fragmentation analysis

Manual analysis of fragmentation has been around for decades. At its most basic level, it consists of taking pictures of the muck pile while placing an object of known size in the shot. This object is then used as a scale: the size of each rock fragment in the photograph is compared to that of the object and, using simple arithmetic, its real size calculated. The most common objects used for this technique include balls, which being spheres have the advantage of having the same measurements when photographed from different angles, and large rulers, which are less prone to roll out of control in the steep slopes that are generally present on muck piles.

Figure 2: Manual fragmentation analysis using a device with 3D capabilities. Source: Gustavo Huerta Valer.

There have been significant advances in manual analysis of rock fragmentation in the last years. At this point, there are many software applications used for processing the pictures taken in the field. Most of them are very accurate and reliable, but still require the intervention of a human analyst to process each picture and make the adequate corrections in lighting and rock boundaries in order to achieve such results.

The latest developments in manual fragmentation analysis include devices that do not require the use of a scale for taking pictures and are even capable of calculating the distance to the muck pile and the angle of its slope. This has a major impact on the safety of the staff on bench due to the ability to circumvent a very dangerous task associated with manual analysis: getting close enough to the muck pile for placing and retrieving the scale object each time a picture is taken.

Besides the safety concerns of getting close to an unstable slope several meters high, frequently made further unstable by the mining process itself, the most obvious limitation of manual analysis is its representability, i.e., whether it is representative of the muck pile as a whole. Since the mining equipment need to be stopped for on bench staff to approach the muck pile, there are very small windows of opportunity to carry out the photography needed without affecting mining operations. In consequence, manual analysis often employs low sample counts due to these restrictions. Even in light of these limitations, manual analysis continues to be a widely extended practice because of its simplicity and little to no hardware required. Still, more and more mining companies are moving away from this type of analysis motivated by increasingly strict safety regulations and their expectations of capturing the fragmentation results on wider areas of the same blast.

3.2. Autonomous fragmentation analysis

Autonomous fragmentation analysis tools aim to provide a continuous stream of PSD data throughout their operation. They usually employ a combination of on-site cameras and processors to capture pictures of the muck pile and analyze the rock fragments present, in a similar manner to software used for manual analysis, but with an autonomous approach meaning that they do not require an operator for sampling or processing data.

Figure 3: Illustration of FRAGTrack$^{(TM)}$ *system. Source: Orica*

At its most basic level, autonomous fragmentation analysis hardware employs a single lens camera to sample the muck pile and interpret the photograph in a 2D representation that is capable of producing PSD data. The shortcoming inherent to this technique is that the processing of these pictures does not take into account the distance between the camera and the muck pile, which leads to an incorrect estimation of rock particles size closer or farther than the calibrated distance. Statistical data on the proximity of the camera to the muck pile demonstrates high variability of this distance, which limits the accuracy of 2D based analysis. Two-dimensional analysis can also be adversely affected by variation in lighting and texture across individual particles, particularly larger ones whose surfaces may consist of multiple facets, potentially leading to those particles being analyzed as if they were comprised of several smaller ones.

The most sophisticated technologies are currently analyzing fragmentation by using 3D photogrammetry, using multiple lenses to provide a tridimensional perspective of the muck pile in an attempt to better characterize the rock samples. These technologies are capable of measuring the distance between the muck pile and the camera which results in a self-calibrated sample in which rock particle size can be evaluated depending on the depth perceived by the processing.

Both techniques have impactful improvements over the manual analysis, such as an increased sample count, which in turn increases the representability of the analysis, and the elimination of exposure to unstable muck piles for on-bench staff. On the other hand, the hardware required for this type of analysis is often costly to own and requires installation work on shovels or other mining equipment to be operational.

4. Contributing factors on fragmentation results

Fragmentation results in the blasting process are highly dependent on several factors; some of which can be fully controlled by the blasting crew, such as the type and quantities of explosives used and the detonation timing, and others that cannot be controlled and are only measured to an extent, such as rock mass fracturing and its compression resistance. In order to properly corelate PSD results to the blasting process, it is necessary to understand which are the main factors and how each one contributes to rock fragmentation.

4.1. Borehole loading

This term refers to establishing the type and quantities of explosive that will be used on each borehole. While there is a large number of combinations available to be applied, most mines will limit the designs to a few possibilities considering the intention of the blasting and the “hardness” of the rock mass. The term hardness is used loosely as it does not refer to the physical property of rocks but to a condition perceived when taking into account many properties, such as the RQD and UCS of the rock mass; these terms are defined in Sections 4.3 and 4.4 below. As a rule of thumb, the more energetic the explosive used, the finer the fragmentation will be as a result. This is also true for the quantity of explosive applied: when used in larger quantities, the same explosives will produce finer fragmentation. We can take the following blast design as an example:

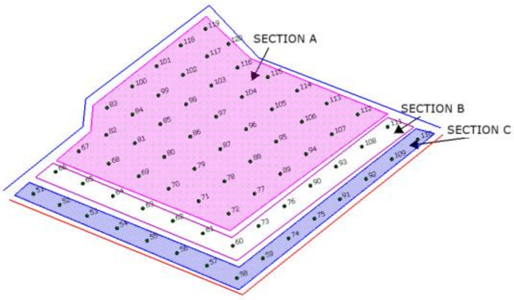

Figure 4: Blast design example. Source: Unnamed large open cut copper mine.

This blast was designed in a large open pit copper operation, with the intention of maximizing fragmentation for ore processing.

- Section A was loaded with 860kg of a high energy explosive, trying to maximize fragmentation.
- Section B was loaded with 600kg of the same explosive, expecting to reduce the impact on the in-situ rock mass delimited by the red line.
- Section C was loaded with 500kg of a low energy explosive in order to minimize damage to the rock mass outside of the blasting limits.

Without taking any other factors into consideration, we can expect a much finer fragmentation on Section A than on Section B and C, as the loading for both is aimed at reducing and minimizing the blasting impact on the remaining rock mass respectively.

4.2. Blast timing

This term refers to the establishment of the borehole detonation sequence and time interval between each detonation. This process follows some general guidelines depending on the desired results for each blast. In general, when trying to maximize fragmentation, short delays are used between consecutive boreholes as this promotes interaction between the compression and tension waves in the rock mass produced by the liberation of explosive energy. In contrast, when it is desired to keep those interactions at a minimum in an effort to reduce the vibrations produced by blasting, longer delays between boreholes are employed.

4.3. Rock mass fracturing

This rock mass property depends on the degree of fracturing, fracture type, fracture spacing, and the angle between fracture systems. Preexisting fractures in the rock mass facilitate the fragmentation process, as less energy is required for achieving the same degree of fragmentation. Most mines would have this property mapped in each blasting project in order to increase or decrease the explosive energy used accordingly. In the following image, an example is presented for the mapping of this property in a bench:

Figure 5: Rock mass fracturing map. Source: Unnamed large open cut copper mine.

The mapping of preexisting fractures in this bench was carried out using RQD, defined as the percentage of intact drill core pieces longer than 10 cm recovered during a single core run (Abzalov, 2016). In this mapping, the orange color represents rock mass with high RQD, pink represents a mid RQD and green a low RQD. Without taking other factors into consideration, we can expect fragmentation on green areas to be much finer than that of orange areas, since green areas have significantly more preexisting fractures than orange areas, when using the same explosive energy.

4.4. Uniaxial compressive resistance

The uniaxial compressive strength (UCS) is the maximum axial compressive stress that a right-cylindrical sample of material can withstand before failing. This is one of the most stated property of rocks and is widely used as an indicator of the rock mass resistance to explosive energy. In the following image, an example is presented for the mapping of this property in a bench, this is the same bench and blast pattern depicted in the previous RQD mapping example:

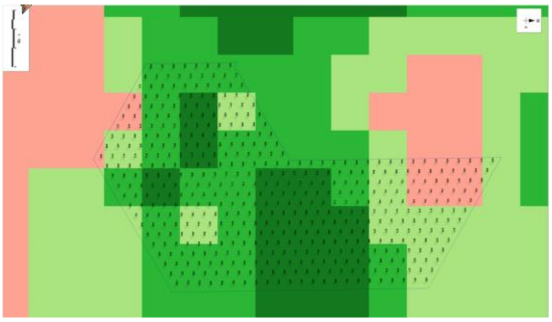

Figure 6: Rock mass UCS map. Source: Unnamed large open cut copper mine.

In this mapping, the pink areas represent a low UCS rock and the green areas a high UCS. The darker the green, the higher the UCS value. As UCS is used to predict the result of explosive energy in the rock mass, we can conclude that blasting rock with lower UCS values will produce finer fragmentation, using the same energy, when compare to a higher UCS rock.

Frequently, the fracturing factor and UCS are used in conjunction to classify the rock mass and determine the degree of explosive energy that should be applied in order to achieve the desired fragmentation in the blasting process.

As seen from the previous examples, a single borehole can be subject to many different factors that influence the fragmentation outcome in a blast. The more detailed the information we can get on each borehole, the more detailed will our PSD results be, as we can only evaluate the impact of the loading design and timing in the context of the rock mass properties that affect said borehole.

5. Developing the next step in fragmentation analysis

In order to maximize the value delivered by our fragmentation analysis, each sample taken from the muck pile should be enriched with detailed information on the contributing factors involved, such as UCS, fracturing, loading factor, among others. These results would not only allow for a detailed evaluation of the performance of the blasting process in the context of the rock mass conditions present, but the prediction of fragmentation results down the line where similar conditions reappear.

For this characterization to be possible, each sample analyzed in the muck pile must be accurately located within the blast boundaries. Since no technology available previously has the capability to georeference the PSD data with sufficient accuracy, a new technology must be developed for this purpose.

5.1. Algorithm

As one of the most advanced fragmentation analysis systems available, Orica’s FRAGTrack™ technology was taken as a base for development. The goal of this process was to expand its current capabilities by creating an algorithm capable of georeferencing each PSD sample. Location data can then be used to match fragmentation results to known information on contributing factors, thereby creating a much more detailed analysis than any other that was previously available.

The algorithm works by establishing a coordinate system based on the shovel’s center-pin “C” and heading “B”, these being provided in local coordinates by the Fleet Management System (FMS) as a high precision real-time data feed. The combination of this information with an initial survey of several key points, including the FRAGTrack™ camera location, allows the calculation of the position and heading of the FRAGTrack™ camera. This concept is made clearer in the following image, which represents a plan view of an operating shovel:

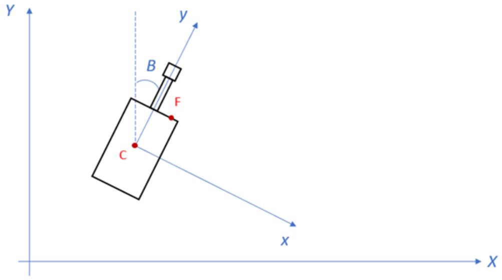

Figure 7: Plant view of the shovel coordinate system. Source: Orica.

In Figure 7, the following points are depicted:

- C: shovel center pin (with location provided by the FMS through an API)
- B: shovel heading (also provided by the FMS)
- F: FRAGTrack™ camera

The following image represents a side view of the operating shovel, with the FRAGTrack™ camera's line of sight centered on a point M on the surface of the muck pile:

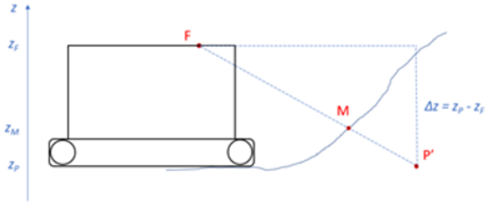

Figure 8: Side view of the shovel coordinate system. Source: Orica.

In Figure 8, the following points are depicted:

- F: FRAGTrack™ camera
- M: muck pile location that needs to be georeferenced
- P': projection of the camera line of sight to floor level

Coordinates of P' are calculated based on the known inclination of the camera and its relative height from the floor level. Using the georeferenced position of F and P', the coordinates for M can be calculated. When cross checking the georeferenced location obtained with the developed algorithm with HPGPS topographic surveying, the difference in each coordinate axis did not exceed 1m, which demonstrates this technique as a working solution with high accuracy.

6. Georeferenced PSD analysis results

6.1. PSD maps

Once the georeferencing of PSD data is made available, the fragmentation analysis results can be integrated with the FMS and other software in order to create detailed PSD data maps. As seen in the image below, a large portion of the bench has been sampled for PSD data that is represented according to their georeferenced location. Each dot on the image correspond to a single processed picture and their fragmentation analysis result using P80 as a KPI.

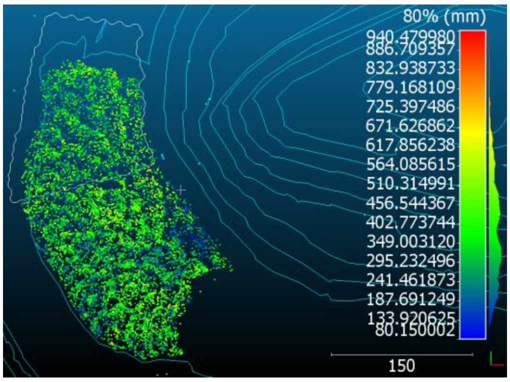

Figure 9: Georeferenced PSD results. Source: Orica.

Furthermore, this data can be used in conjunction with designed and real borehole loading information to create detailed fragmentation analysis represented in Voronoi diagrams.

6.2. Voronoi diagrams

To construct the Voronoi diagram of a plane, we use generating point as reference to subdivide it into convex polygons in a way that each polygon contains exactly one generating point and each point inside the polygon is closer to its generating point than to any other.

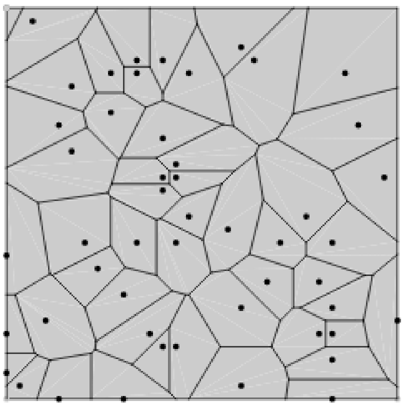

Figure 10: Voronoi diagram. Source: https://mathworld.wolfram.com/

When applying these principles to a blasting project, we can use each borehole as a generating point to sub divide the blasting boundaries into polygons. Each polygon, will contain a region of the rock mass that is closer to one borehole than to any other. In consequence, the fragmentation results for each polygon will be more closely related to the loading of its generating borehole. We can use these diagrams to illustrate how the loading factor is distributed in a blasting project.

In the following figure, a color scale was used to represent the powder factor of the design loading in a blast using a Voronoi diagram. Since this diagram only includes the intended loading of the blast when the process was designed, it should be updated once the loading process in the field has concluded. Usually, bench conditions such as irregular or missing boreholes and fractured rock mass or even human intervention have considerable impact on how the blasting projects are actually loaded.

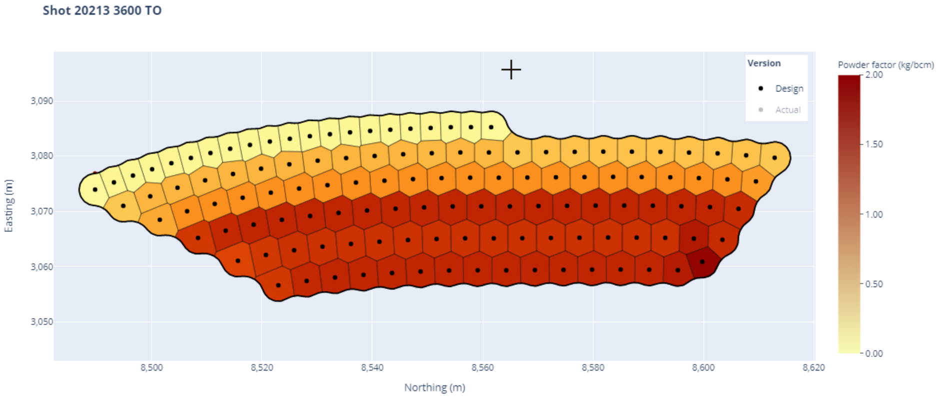

Figure 11: Example of Voronoi diagram for design loading. Source: Orica

In the following figure, we have an updated Voronoi diagram for the same project, this time, using the actual loading carried out on the bench.

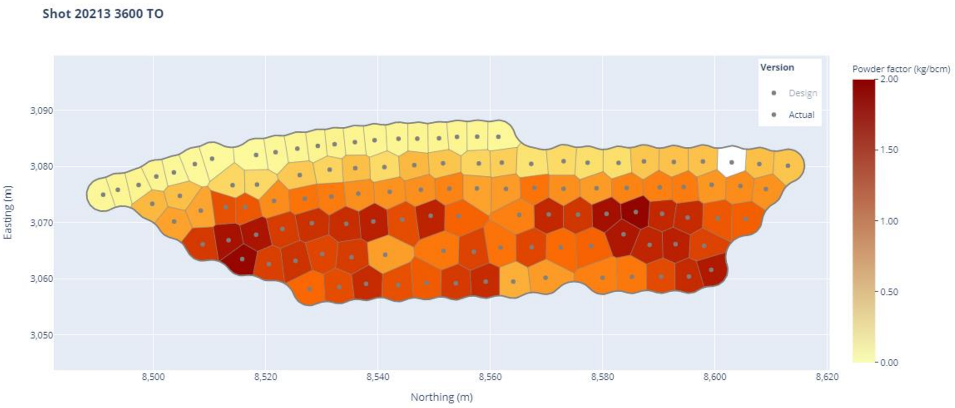

Figure 12: Example of Voronoi diagram for actual loading. Source: Orica.

Using georeferenced PSD data, an alternative diagram can be created, in order to depict the average results for each polygon. The following picture shows the corresponding Voronoi diagram as a work in progress, since there are still boreholes without PSD information as they had not been analyzed at the time of its making. In this case, the average P80 in each polygon was represented using a color scale for easier identification of the results.

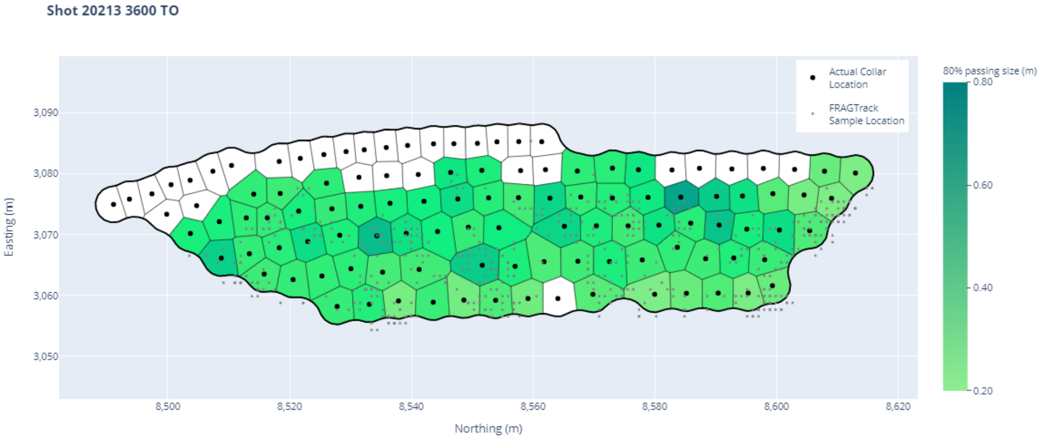

Figure 13: Example of Voronoi diagram for georeferenced P80 results. Source: Orica.

From the last two diagrams, a detailed analysis can be made that corelates the fragmentation of each polygon to the corresponding explosive loading of its generating borehole. This analysis can be further enriched by taking into account available information on contributing factors that correspond to the rock mass, such as UCS and pre-fracturing data.

7. Conclusions

Through the development of an algorithm that improves on the current capabilities of the autonomous fragmentation analysis system FRAGTrack™, georeferenced coordinates of PSD samples can be made available. Requiring only a live high-precision feed of the center pin location and heading of the shovel, provided by the FMS, along with an initial survey of key points pertaining to the shovel and FRAGTrack™ camera, it is both simple to implement and highly accurate.

The ability to georeference the fragmentation samples measured on the dig face while mining unlocks unprecedented value for mining operations. This allows continuous monitoring and understanding of blast performance as well as accurate association of fragmentation data to key performance metrics such as instantaneous dig rate and the geological data of the muck pile. The data produced is relevant for many teams in various ways:

- Drilling and Blasting teams benefit from this technology by identifying issues at a sub blast level, being able to quickly review oversize and undersize zones, and correlating fragmentation against blasting parameters on a borehole-by-borehole basis.
- Short term planning and Blast Design teams are able to correlate fragmentation over geo domain data and unlock the ability to continuously improve blast designs to achieve target outcomes.
- Ore control teams get accurate data for the milling operation that can be correlated to grade and hardness, and the ability to target optimal fragmentation for the ore body in the blast designs.

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