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SIMULATION AND EXCAVATION OF HORIZONTAL DEVELOPMENTS IN BLOCK/PANEL CAVING MINING

TESIS PARA OPTAR AL GRADO DE MAGISTER EN MINERÍA

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SIMULACIÓN Y EXCAVACIÓN DE DESARROLLOS HORIZONTALES EN MINERÍA DE BLOCK/PANEL CAVING

Este trabajo de investigación versa sobre el sistema de excavación en roca mediante perforación y tronadura en múltiples frentes y considera dos enfoques: en el primero se investiga de manera global el sistema de excavación convencional con el uso de explosivos desde un punto de vista de planificación a fin de cuantificar la eficiencia del sistema constructivo de túneles. En el segundo se ahonda sobre el proceso de arranque mediante explosivos identificando para ANFO y emulsión el rol que tienen los explosivos en el avance y las interferencias.

Se aplicaron técnicas de simulación de eventos discretos en el proceso de planificación de los desarrollos horizontales en múltiples frentes para un caso de estudio de una mina explotada por Panel Caving, encontrando que para este caso particular, el ciclo de avance está altamente influenciado por las interferencias entre operaciones unitarias, de forma tal que para aumentar el rendimiento de avance no solo es necesario optimizar las actividades del ciclo individualmente, sino que es preciso una disminución en los tiempos perdidos por interferencias. El modelo de simulación fue construido y calibrado en un software de simulación especialmente diseñado para minería: SimMine. Los inputs para el modelo fueron obtenidos en terreno en un estudio previo e incluyeron tiempos de operaciones unitarias, así como de interferencias, estos fueron representados a través de distribuciones de probabilidad triangulares para cada uno de ellos. Las interferencias halladas entre operaciones unitarias representan las mayores pérdidas de tiempo.

En el segundo estudio, se analizó el rol del explosivo para el arranque de roca en los desarrollos horizontales en múltiples frentes. Con lo cual se pudo contrastar el uso de ANFO y emulsión en términos del número de tiros, dilución de gases tóxicos (lo que representa menor tiempo de ventilación), avance por disparo y sobre-excavación. Los datos para el análisis comparativo se basan en pruebas de tronadura realizadas en terreno a escala piloto e industrial, de las cuales se obtuvo que con la emulsión se alcanza una mayor eficiencia de avance, se necesita menor cantidad de tiros y menor tiempo de ventilación que con el ANFO. También se evidenció que la sobre-excavación está influenciada por la concentración de carga lineal en los tiros de contorno.

Del primer caso, se concluye que planificar con variabilidad en los tiempos de proceso, así como captar las diversas interferencias, arroja rendimientos cercanos a la realidad, convirtiéndose la simulación en una herramienta de apoyo en la toma de decisiones en la planificación de los desarrollos horizontales en múltiples frentes. En el segundo caso, se evidenció que existen mejoras en la operación de tronadura en desarrollos horizontales, de acuerdo a las variables medidas, al comparar el desempeño de la emulsión con respecto del ANFO.

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SIMULATION AND EXCAVATION OF HORIZONTAL DEVELOPMENTS IN BLOCK/PANEL CAVING MINING

This research explores the underground excavation method of drilling and blasting on multiple faces with two objectives. First, through a global investigation of mine planning, the conventional excavation system using explosives is analyzed to quantify the efficiency of tunnel construction. Secondly, the drilling and blasting process is explored to compare advance performance when applying ANFO versus emulsion in the process.

To achieve the first objective, discrete event simulation techniques were applied in the short-term planning process of horizontal developments in a case study of a mine operated by Panel Caving. The simulation model was built and calibrated in simulation software especially designed for mining: SimMine. The inputs for the model were obtained from the field in a previous study and included unit operation times, as well as interferences. In this particular case, field study showed that the excavation cycle was unnecessarily extended by the interference between unit operations. In fact, the interference found between unit operations represented the biggest losses of time. Then, to increase the forward performance of excavation, it was necessary not only to optimize the individual activities of the cycle, but also to reduce the time lost due to interferences.

For the second objective, the role of explosives in the blasting of horizontal developments on multiple faces was analyzed. For this study, the use of ANFO and emulsion was contrasted in terms of the number of boreholes, dilution of toxic gases (which represents less ventilation time), advance per round and overbreak. The data for the comparative analysis is based on blasting tests carried out in both small- and industrial-scale tests. Results showed that using emulsion a greater efficiency of advance was reached, with fewer boreholes and less ventilation time needed than with ANFO. It was also observed that overbreak was influenced by the concentration of linear charge in the contour boreholes.

In the first case, it was concluded that planning with variability in process times, as well as capturing the various interferences, yielded returns close to reality, making the simulation a support tool for decision-making in planning. In the second case, improvements were observed in the blasting operation and in advance performance in horizontal developments when using emulsion versus ANFO explosive.

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Chapter 1

Introduction

Underground Mining development can be defined as the set of activities for tunnel construction including mechanical activities, electrical activities, instrumentation, engineering and infrastructure assembly -of different levels or sectors- that will incorporate an area and allow for the continuity of the mining process (Díaz & Morales, 2008). Compliance with the mine development plans is particularly important in order not to generate delays at the start of production; according to Toro et al. (2016), compliance depends significantly on the short-term planning of work to be developed.

Within the mining development phase, the construction of horizontal developments is one of the key processes. Horizontal development allows access to the orebody and will enables the rest of the mining development work to proceed, such as ore passes, civil construction and opening of draw points. The planning and execution of horizontal developments present challenges and opportunities in terms of progress efficiency, especially on multiple faces. On many occasions, the critical route in production is limited by the velocity of progress of the development phase (Salgado, 2012), and this progress, is directly related to two factors: the time spent in the execution of unit operations and time lost due to interferences.

Time required for unit operations could be reduced using a variety of methodologies and technologies oriented towards the rapid construction of tunnels through mechanizing the processes involved in blasting. Using explosive emulsions also presents significant advantages in relation to the traditionally used ANFO, which in often preferred over emulsion usage particularly in Chile.

Time lost because of interference during the execution of unit operations also represents an important factor in mine operation. Repetitive events or interferences, such as lack of materials, lack of workers, closure of drifts, etc., can significantly impact the progress of the excavation cycle, causing it to take longer to complete. Although increasing the efficiency of the individual unit operations is fundamental for the advance of the horizontal developments, the completion of the full excavation cycle may also be restricted due to time lost through interferences. Therefore, identifying and quantifying interferences can influence the velocity of progress of the horizontal developments to generate more realistic mine planning.

The aim of this study of short-term planning is to understand the system and then to model it in order to deliver progress goals according to the reality of the mine. It is suggested that incorporating inputs of time analysis that consider the time variability in the processes and time lost with the operational interferences will provide a more realistic model of mine progress. Secondly, an analysis of the progress scale considering the type of explosive used was done to evaluate the role of explosives in the dilution time of gases, the efficiency of advance, the number of boreholes and the overbreak. This information should help to increase efficiency in underground mining projects.

To evaluate the impact of interferences and time involved in mine processes, and also to evaluate the impact of using emulsion explosives in the horizontal developments, two study cases were conducted at the production level of two different sectors, but with similar conditions for the horizontal development construction. The two sectors studied were the Esmeralda and the Pacífico Superior, both sectors belonging to the División El Teniente (DET). The production level of each of the sectors considers a Teniente layout, which is composed of parallel drifts –haulage drifts– separated by 30 m, intersected by a set of galleries –production drifts– separated by 17 m or 20 m, and at a 60° angle. In DET, a conventional excavation cycle is used to construct the tunnels.

The software used for the simulations was SimMine. This software was specifically developed for mining purposes. It is easy to use because it does not require knowledge of programming and the simulations can be run quickly. It also uses minimum memory and requires little computation time.

Thesis Outline

This research is based on articles and is divided in the following chapters:

Chapter I contextualizes the study and lays out the hypothesis, objectives and scope of this investigation.

Chapter II presents a literature review of previous relevant studies that have been conducted using discrete event simulation techniques in the planning of horizontal developments; additionally, the state of the art of the explosives ANFO and emulsion, is presented.

Chapter III is a paper published in Proceedings of UMining 2018. "Simulation of horizontal developments on multiple faces considering interferences". The objective of this paper is to present the discrete event simulation technique as a support tool in the short-term planning of the horizontal development tasks of multiple faces. The model integrates operational interferences and variability in the processes with input data obtained from a time-study performed in the field.

Chapter IV is a paper submission to Tunneling and Underground Space and Technology (ISI Journal with Impact Factor: 2.4). "A comparison of Emulsion and ANFO usage in the horizontal development process at El Teniente". The article shows a comparative study of the performance of emulsion and ANFO in terms of gas dilution, advance efficiency, number of boreholes and overbreak. The data were collected in the field through the application of trial and industrial blasting tests.

Chapter V presents a summary of the conclusions and recommendations for future work.

Appendices present the simulation results of the emulsion usage in horizontal development performance, the database and their statistical analysis for both papers and the work functionality of SimMine software.

Problem statement and hypothesis

Delays in development activities can have a significant impact on the economic value of a mining project because these delays result in an extension of the caving entry. Two important factors cause mine development plans to suffer constant non-compliance:

- Lack of integration of variability in the processes. Projections are usually made based on averages of historical data.
- Lack of inclusion of interference and operational restrictions. This is especially problematic in Block/Panel Caving mines, in which production and development often coexist at the production level. For example, sharing resources such as ore passes for evacuation of muck generates interruptions for production.

Adequate planning must consider, among other factors, that the work previous to production is ready on time to minimize uncertainty in the progress goals. However, because mining operations present intrinsic uncertainties and random behaviors, insuring that activities proceed according to a time plan is difficult. This is where the discrete event simulation becomes a useful tool. This tool models the behavior of the system including important real-world uncertainties and variability existing within unit operations.

To improve mine operation it is also necessary that the processes involved in the construction of the developments be evaluated constantly to identify opportunities that allow the activities of the excavation cycle to be more efficient and effective. One of the most important aspects of the method of tunnel construction by drilling and blasting is the selection of the type of explosive, since the subsequent activities in the excavation cycle will depend on the performance of the blasting. Traditionally the explosive used in Chile has been ANFO; however, the advantages of using alternative explosives such as emulsion make it feasible for use in confined environments.

As will be shown through the comparative study, advantages of the use of emulsion involve a smaller number of boreholes, which means a decrease in the amount of explosives used as well as a decrease in the drilling time, greater advance per round, and a smaller volume of toxic gases, which results in faster evacuation of the gases and therefore reduces ventilation time.

In summary, two hypotheses are analyzed:

Hypothesis 1: Horizontal development targets would be more realistic if variability of processes and interferences could be incorporated in the mining planning.

Hypothesis 2: The use of emulsion explosive for horizontal developments provides better blasting performance in terms of ventilation, advance and overbreak. These variables are critical in the development of tunnels and can be evaluated to observe their effect in the excavation cycle.

Objectives

General objectives

The present research has two fundamental objectives:

- To implement discrete event simulation techniques as an alternative tool within the development planning for a Panel Caving mine
- To compare ANFO and emulsion performance in field testing in horizontal developments on multiple faces.

Specific objectives:

- Carry out a time study in the field, which includes the measurements of the time involved in each of the unit operations, as well as the time lost due to interferences on multiple faces.
- Construct a simulation model of the horizontal developments in the mining development phase (study case: Esmeralda).
- Identify and include interference and operational restrictions in the simulation model based on data gathered in the field.
- Analyze explosive field tests statistically, considering as baseline the blasting carried out with ANFO in contrast to those conducted using emulsion.
- Compare the performance of the explosive ANFO versus emulsion in terms of dilution of toxic gases, effective advance, number of boreholes and overbreak (study case: Pacífico Superior).

Scope

For the simulation of horizontal developments of multiple faces:

- The simulation models the construction of horizontal developments over a period of 30 days at the production level of a mine operated by Panel Caving.
- The construction of the simulation model was carried out in the discrete event simulation software designed for mining: SimMine.
- In the simulation model, the construction of the horizontal developments is conducted by a conventional drill and blasting method and does not include the development of vertical works, civil construction or interaction with other levels of the mine.
- The simulation allows for comparison of advance performance considering the use of two explosive types: ANFO and emulsion in horizontal developments.

For the comparisons of the ANFO and emulsion explosives:

- Statistical analysis of the field tests in terms of toxic gas dilution, advance efficiency, number of boreholes, and overbreak, based on the information collected by Orica and CODELCO.
- Comparison of the performance of each type of explosive in horizontal developments (specifically haulage and production drifts) in the production level of the Pacífico Superior sector.
- Use of the baseline of tests carried out in the Diablo Regimiento sector to compare the efficiency of progress with the tests carried out in the Pacífico Superior sector, both belonging to the DET and with similar geological conditions.

Chapter 2

Literature Review

The first part of this literature review has the purpose of understanding the principles of research carried out over time, applying the discrete event simulation in the planning of underground mining. The second part focuses on a state of art review regarding the performance of the explosives object of the study: ANFO and emulsion.

Discrete Event Simulation (Banks et al., 2010)

By definition, simulation is the imitation of the operation of a real-world process or system over time. Whether done by hand or on a computer, simulation involves the generation of an artificial history of a system and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system.

The behavior of a system as it evolves over time is studied by developing a simulation model. This model usually takes the form of a set of assumptions concerning the operation of the system. These assumptions are expressed in mathematical, logical, and symbolic relationships between the entities, or objects of interest, of the system.

On the other hand, the Discrete Events Simulation (SED) is the modeling of systems in which the state variable changes only at discrete set of points in time. The simulation models are analyzed more by numerical methods rather than by analytical methods. In the case of simulations models, which employ numerical methods, models are “run” rather than solved – that is, run artificial history of the system is generated from the model assumptions, and observations are collected to be analyzed and to estimate the true system performance measures. Real-world simulation models are rather large, and the amount of data stored and manipulated is vast, so much runs are usually conducted with the aid of a computers.

Application of discrete event simulation to underground mines

DES techniques have been used in underground mining since 60’s up today, proving to be very useful in support of the planning process. The first examples of mine simulations focused on queue problems, the work by Rist (1961), is a most important contribution to literature of the age. Rist’s problem was taken from an actual underground molybdenum mine, where his model was used to determine the optimum number of trains to have on a haulage level. Falkie & Mitchell (1963) studied the complex underground road for a coal mine in Pennsylvania; this work laid the groundwork for how Monte Carlo methods are incorporated into stochastic simulation models (Sturgul, 2015). Since 80´s the use of the simulation techniques in the mining industry has grown due to the incorporation of new programming languages. This has allowed a greater robustness in the simulations including the simulation of complete levels; an example of this is the study by Kurlenya & Kryzhanovskii (1989), who carried out simulations of the production plans for underground mines, showing the potential of the simulation tools.

Since 90´s and currently, the use of different programming languages and the inclusion of the animation have made the use of simulators more interesting for mining industry. Brunner et al. (1999) carried out a discrete event simulation model used to support the decision making process through comparisons between two performance mining simulation models with different level of detail. The study was conducted at CCSM (Copper Cliff South Mining) located in Sudbury, Ontario, Canada. For the investigation, the software Automod was chosen. First, in 1995 a model known as the "DP" model was created based on the logic for the development and production of an orebody upstream of the dump points. Development logic is modeled in that way: a fixed number of “development resource” is deployed throughout the model, a development resource is treated as a unit containing all crew and equipment needed to advance a single face. Any face determined to be physically and logically accessible claims one of these resources or, if none is available, is added to a waiting list. Whenever a crew resources become available it scans the list for the highest ranking drift to start next. Once there are working groups available, construction begins, with a given advance rate (input). After several revisions, the "revised DP" model was obtained. The latter model has significant changes with respect to the original: the advance rate was replaced with the process cycle time input and became an output; a "foreman controller" was implemented to make crew and equipment allocation decisions both at the beginning of each shift and also when other state changes occur such as the freeing of a resource; and a "management controller" was implemented to direct the initial allocation and long-term movement of equipment among development complexes. The most important conclusion of this study is that the SED turned out to be a very useful analysis tool to contrast the models and support mining engineers in making the correct decisions by combining different scenarios (production methods, equipment and staffing).

Ruciman et al. (1999), used discrete event simulation technique (software: WITNESS) to make comparisons of the advance rate among four tunneling development alternatives for the CCSM mine: drilling and blasting with conventional equipment, drilling and blasting with tele-operated equipment, Penetrating Cone Fracture Excavation system and simultaneous system of excavation and material handling. After the simulations were carried out, it was concluded that, drilling and blasting with tele-operated equipment system can increase the advance rate, showing that simulation is an effective tool for assess different technologies for underground mining.

Vargas et al. (2013) showed that a simulation methodology based on the Monte Carlo method is very effective tool for planning to estimate the time required for the excavation of tunnel, and this is because operating through probability distributions, incorporates the inherent variability in planning processes. To use the Monte Carlo method, the unit operations involved in a conventional underground excavation cycle are identified and assigned a probability distribution with which the different scenarios will be simulated by generating random numbers, these numbers will deliver the different times for each operation and finally, the sum of the simulated times per unit operation give the cycle times that it is possible to obtain. This makes it possible to simulate the total time of the excavation.

Salama (2014) combined the simulation of discrete events and Mixed Integer Programming (MIP), to evaluate different haulage systems in underground mining, including diesel and electric trucks, shafts and belt conveyors. Discrete event simulation was used to estimate mine production for different haulage systems, and the results were used to calculate appropriate mining cost. MIP was then used to generate the mining plan and the optimal production schedule. In the first case study, the ore haulage and transportation system was simulated to determine the number of trucks per LHD for the mine production, to increase the mine output and to evaluate the possibilities to reach the assigned production targets. In the second case study, four transportation alternatives were simulated: diesel trucks, electric trucks (both operating on inclined with 10% slope), shaft (with 15-ton skip) and inclined belt (20-30% slope) at different depth levels: 1000 m, 2000 m and 3000 m for; under two scenarios: current energy prices and future energy prices (three times higher than current ones) to analyze the impact on the cost of the energy requirements associated with each system. In the third case study, the discrete event simulation was used as a tool to obtain the number of LHDs required to transport 300,000 tons of ore for a period of 3 months from two different orebodies up to two different ore pass, located 250 m from each orebody. The fourth case study was carried out in a mine operated by Sublevel Caving, which simulated the production of electric and diesel LHDs according to their energy consumption and gas emissions (for diesel).

Botin et al. (2015) proposed a tool that combines discrete event simulation and Program Evaluation Review Technique (PERT) in order to optimize the size and performance of the fleet for the construction of horizontal developments, thus minimizing the duration and cost of the preparation stage. The tool was validated at the Chuquicamata mine. The simulation program was adapted in order to calculate the duration of construction for all possible equipment combinations, considering a maximum of five pieces of equipment per unit operation. In parallel, a financial risk model was developed to quantify the variation of project Net Present Value (NPV) associated with the variability of production start-up. This NPV model was used to evaluate scenarios with varying equipment fleet sizes, and to determine the optimum development equipment fleet. The optimum fleet was determined as the point of economic equilibrium between the additional capital expenditure required to purchase new equipment and the NPV increase resulting from the anticipation of the start-up date which may be achieved.

Contreras (2016) made a simulation model of horizontal developments in Promodel software. This consisted of creating a layout composed of four parallel drifts, joined by a main header, and adding interferences to quantify the impact of these compared to the advance rates. Interferences considered were: closure of drifts, transfer of workers, availability of services, oil charging, scheduled maintenance, failures and learning curve. Four scenarios were evaluated: rock conditions (good, fair, poor), distance and number of dumping points, configuration of the work crew and variation of the number of active work faces. Finally, from the study, a useful model for comparing scenarios and quantifying the impact of interferences separately in the system was obtained.

Discrete Event Simulation using SimMine

Currently there is a wide range of software and programming languages for simulations with general and specific purposes; in this study discrete event simulation software designed for mining: SimMine was chosen. SimMine is a very useful tool to represent the behavior of mining processes over time. There are important cases studies achieved with this program, among them:

Botha & Nichol (2009) carried out a simulation model to analyze the effect of different scenarios in order to reduce the construction time and therefore, maximize the horizontal developments rate in Cullinan Diamond Mine. The scenarios simulated were: multi-blasting in the shift, increase the number of drill rig equipment by one more unit, increase the number of drill rig and loader by one more unit at the same time and perform 12-hour shifts. The study showed that the software can quickly reveal the bottlenecks in the base case and analyze the impact of alternative scenarios on the development rate. For this particular case, the performance of the developments increased significantly by combining the four proposed scenarios.

Greberg & Sundqvist (2011) did an analysis in the pre-feasibility stage for the underground operation of Cadia East, whose main objective was to verify the initial plans for the development stage. Under the restriction that some fronts had to be developed on a specific date, in such a way that the construction of new ventilation shafts could begin; Different scenarios were simulated, including the number of active fronts in parallel, prioritization of work areas / fronts and different starting dates for the fronts. As a result it was obtained that when the number of active fronts increased at a certain point, it was impossible to develop certain areas of the mine within the time allowed, being necessary to prioritize the number of work areas / fronts, since having many fronts working at the same Time generates bottlenecks in loading and transport activities.

Li (2012) studied the advance rate in the development stage for the Oyu Tolgoi mine. Two simulation models were built: the first included four years of horizontal development and was used to evaluate the drifts and massive excavations (such as crushing rooms) performance construction, based on different sections and fortification requirements; the model was calibrated and validated with the advance (in meters) of the horizontal developments of the mine for a period of 11 months, all the results of the simulations were within a 5% difference in respect to the real one. The second model considered 3 years of horizontal developments and was used to analyze in detail the use of equipment fleet; the model was calibrated with the advance, analogous to the previous case, however it was not validated correctly due to some unexpected delays and equipment failures in the mine during the validation period. As a result of the simulation, the possible advance rates for each of the established sections were obtained; as well as, it was possible to determine the use of the equipment and from that, calculate the ventilation requirements. However, at the advance values reported by the simulation model, a reduction of 25% was applied to be closer to the historical values of the benchmarking performed with other caving operations, since the model supposes an over-utilization of the equipment and does not contemplate traffic interactions.

Salama & Greberg (2012) used simulation techniques to model the loading and transport operation (LHD-truck), for the production of a mine operated by Sublevel Open Stoping in order to optimize the number of trucks. The number of LHDs was fixed, but the number of trucks was increased from three to nine. In the model, the path distance traveled by trucks from the stopes to the dumping point in each level, was simulated. The result suggests that to improve the monthly production of ore, one LHD can be assigned to load two trucks when working in the stopes located close to the dumping point, and a fleet of three trucks are needed for the stopes located on the lower levels of the mine.

State of the art of explosives: ANFO and emulsion

From a practical point of view, explosives are simply materials that are intended to produce an explosion, i.e., to have the ability to rapidly decompose chemically, thereby producing hot gas which can do mechanical work on the surrounding material (Persson et al., 1994). In general, explosives break the rock because of two factors: the impact of the shock wave and the expansive effect of the high gas pressure formed during detonation.

The explosives object of this study: ANFO and emulsion are classified (see Figure 2.1) within the Highly Explosive as Secondary Explosives, which need a primer to be able to detonate. According to Persson et al. (1994), even though the ANFO and the emulsion may contain the same chemical energy, their field performance may differ, and this is extensively due to differences in detonation velocities. The ANFO consists of a solid phase, formed by prills (granules of Ammonium Nitrate) with a diameter around 2 mm coated with the fuel oil; the emulsion, meanwhile, is a liquid salt solution (oxidant) of Ammonium Nitrate, occasionally Calcium or Sodium Nitrate, made up of 0.005 droplets mm, each droplet of oxidant is surrounded by a thin film of fuel, which consists mainly of gasoline and waxes, in many cases, emulsifying agents are incorporated to stabilize the mixture, so that the components do not separate and the Nitrate in solution does not crystallize.

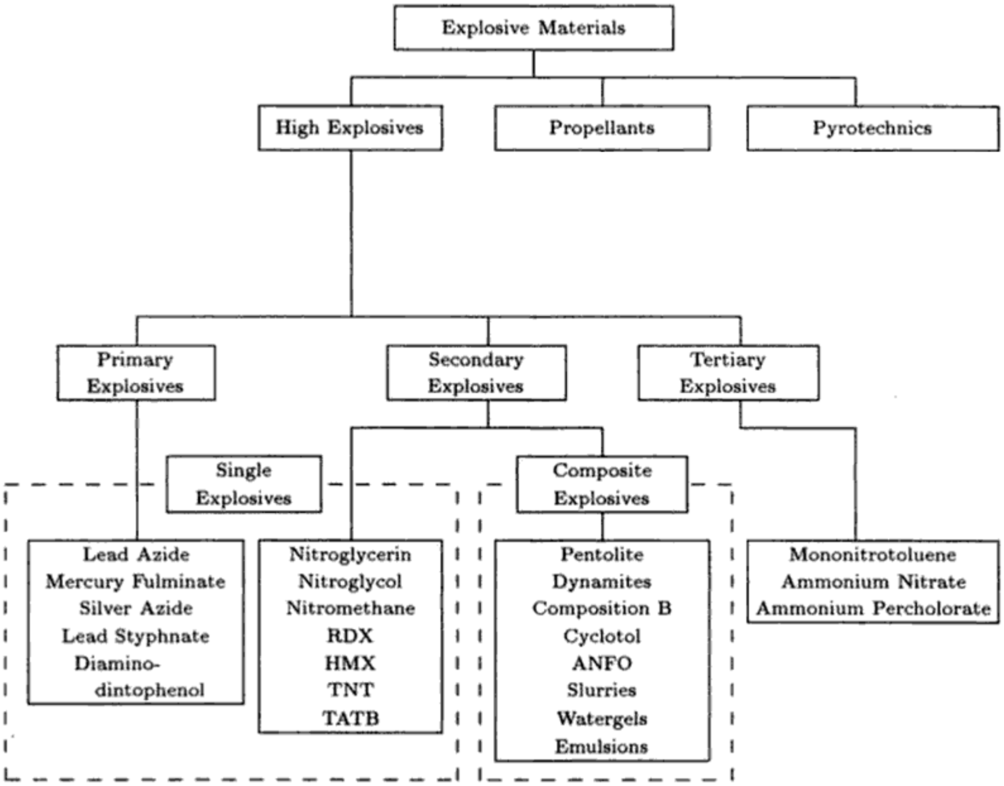


Figure 2.1: Classification of explosive materials (Person et al., 1994)

The ANFO is commonly used in the mining industry because of its power, relatively low cost and ease of manufacturing and handling. The main disadvantage of the ANFO is not water resistant and its performance is negatively affected when it comes into contact with it. On the contrary, the emulsion has an outstanding resistance to water, due to the thin oil film that covers the oxidant, which does not allow contact with water. Additionally, it has greater flexibility compared to the adequacy of its physical properties to suit its application, being able to be formulated with a range of viscosities from reasonably low, such that they can be easily pumped, until highly viscous, if required. The density can be controlled by introducing air into the product; this is achieved by using a gasifying agent or by the addition of glass microspheres (López et al., 1995).

Velocity of detonation

The detonation in an explosive column (contained, for example, in a blast hole) involves the passage through the column of a chemical reaction front. The front is driven through the column, by the products of the reaction, at a superacustic velocity, called the detonation velocity -VOD- (Brady & Brown, 1994). In Table 2.1, the VOD of each type of explosive, corresponding to a given oxidant particle diameter, can be observed. This reflects the strong dependence of the efficiency of the reaction with the particle size (López et al., 1995).

Table 2.1: Characteristic size of oxidizers (Bampfield & Morrey, 1984)

Explosive	Size [mm]	Form	VOD [km/s]
ANFO	2000	Solid	3.2
Dynamite	0.2	Solid	4.0
Emulsion	0.001	Liquid	5.0 – 6.0

The VOD is a key indicator of the performance of the explosive and is influenced mainly by the diameter of explosive column (borehole diameter), confinement, density, primer size and type, sensitizing agent(s) and sleep time in borehole (Dowding & Aimone, 1992; Chiappetta, 1998; Hopler, 1998). Particularly, is important to mention that the VOD changes if the diameter of the explosive column also changes. The velocity decreases as the diameter of the column decreases. This effect is caused by pressure fall at the side of the column. When the diameter is large, the losses are small in relation to the production of energy at the wave front. When the column diameter is small, the energy losses are larger relative to the energy generated in the wave front (Cooper, 1996). It is also known that VOD increases with the confinement. The experimental results conducted by Sun et al. (2001) and Essen (2004) indicate that VOD of the emulsion is greater than ANFO and it is reached at a smaller diameter; and that as confinement increases for a given diameter of explosive column and type of explosive, the VOD increases, respectively.

Another factor to consider, in terms of VOD, is the relation between the sonic velocity of the rock (P-wave). To obtain high efficiency in the blasting, it is necessary that the effective VOD of the explosive is greater (or equal) to the P-wave velocity of the rock. The VOD is proportional to the energy released, and increasing its value produces a better stress distribution. In the case that the VOD is less than the P-wave velocity of the rock, the undetonated explosive in front of detonation could be compressed by the stress waves, this could cause the explosive undetonated fail to detonate. If there are additional primers in these parts, they may possibly be damaged. This was confirmed by the tests conducted by Farnfield et al. (2011) and Mencacci et al. (2003). It is therefore advisable to choose an explosive, whose detonation velocity is greater than or equal to the velocity of the P wave of the rock (Zhang, 2015).

Oxygen balance

In general, for explosives, the chemical composition, as well as the homogeneity and its resistance to water, influences the volume of noxious fumes. Commonly, it is estimated that for each 1 kilo of explosive detonated, about 1,000 liters of gaseous products are formed, 5-10% of which consist of pollutants, mainly carbon monoxide and nitrous gases (Johansson, 2000).

In an explosive the oxygen balance determines the fraction of toxic gases. According to Music (2007), the oxygen balance can be defined as the difference between the oxygen atoms present in the mixture required to fully oxidize the reducing elements, in order to produce the compounds whose heat of negative formation releases the energy which is used in the blasting. The oxygen balance depends on the chemical composition (especially content or oxygen requirement) of the oxidants and reducers that make up the explosive.

The composition of an explosive is balanced when the oxygen contained by the ingredients combines with the carbon and hydrogen content to form carbon dioxide and water. If there is insufficient oxygen (a negative oxygen balance), the tendency to form carbon monoxide is increased. If there is an excess of oxygen (a positive oxygen balance), oxides of nitrogen are formed. Oxygen balance is kept within specific limits to give the lowest practical content of toxic gases. An explosive that has acquired excessive moisture content due to unfavorable storage conditions or to water in borehole will produce a greater percentage of toxic fumes than the same weight of explosive with normal moisture content detonated in a dry borehole (Bhandari, 1997). All emulsion explosives emit a markedly smaller volume of toxic fumes compared to ANFO and nitroglycerin explosive, especially when it comes to nitrous gases (Johansson, 2000).

Advance

Tunnel blasting is characterized by no a priori free surface, except the tunnel front, so it is necessary to create an empty hole along with charged holes, which will break the remaining charges of the section to form the burn cut. Known the diameter of the empty hole, the advance by blasting can be calculated by the equation proposed by Holmberg (1979). For economy, the total depth must be used, the mining tunnels become very expensive if the advance is much lower than 95% (equation 2):

$$\mathrm{H} = 0.15 + 34.1\emptyset - 39.4\emptyset^2 \tag{1}$$

$$\mathrm{I} = 0.95\mathrm{H} \tag{2}$$

Where

H: theory advance [m]

I: real advance considering 95% of efficiency [m]
Ø: diameter of relief hole [m]

When the burn cut have more than one relief hole, instead of just one of larger diameter, equation 1 is still useful, calculating the diameter as shown in equation 3:

$$\emptyset = d\sqrt{n} \tag{3}$$

Where
d: diameter of relief hole [m]
n: number of holes [units]

As can be seen in equation 1, the theoretical advance length is directly related to the diameter of the empty hole; however, it must be taken into account that when very large drilling diameters are used (greater than 250 mm), equation (1) underestimates the length of advance that can be reached. For example, in diameters of 250 and 300 mm, applying equation 1 and 2, the length of advance would be 5.9 and 6.4 m respectively. However, with these diameters, major advances have been made. An example of this are the tests carried out at LKAB in Malmberget (Niklasson & Keisu, 1993; Fjellborg & Olsson, 1996), where advances of 7.5 m and 7.1 m were achieved with an empty hole diameter of 300 mm and 250 mm respectively, meaning an efficiency of 97% and 93% in each case. In these tests it was concluded that the efficiency of the blast decreases as the diameter of the empty hole decreases (Holmberg et al., 2001).

In short, equation 1 is valid for empty hole diameters of 0.05 m to 0.25 m and blast hole deviation less than 2% (Holmberg et al., 2001).

Overbreak

The overbreak is the breakage, dislocation and significant reduction in the rock mass quality beyond the design perimeter of the excavation (Forsyth, 1993). In tunneling, overbreak is one of the most frequent problems and produce unfavorable effects. On the one hand, the number and extension of new fractures in the rock generates extra disturbances to the rock mass and on the other hand it interferes with the performance of the unit operations after drilling and blasting, such as, greater amount of mucking, and therefore greater time to execute this processes, and more consumption of materials for fortification. The generation of over-excavation can occur due to several factors, among them the distribution and characteristics of the explosive, blast hole deviations, the frequency, orientation and opening of the discontinuities and in general the geomechanics conditions of the rock mass. In this particular study, the overbreak has been revised from the point of view of explosive charges.

Explosives characteristics play a vital role in producing blast damage. Explosive products release their energy and interact with rocks in different ways due to the difference in their constituents and reaction characteristics (Singh, 2005). The type and quantity of explosives used mainly in the contour of the excavation significantly influence the over-excavation, so it is necessary to apply controlled blasting practices in the perimeter of the excavation, in order to restricting the number and extension of new fractures in the rock. There are two methods industrially important used in the perimeter blasting control of the excavation: smooth blasting and pre-splitting (Brady & Brown, 1994).

Different authors agree that the smooth method decreases the overbreak, aiming to improve the distribution of the explosive energy, in order to reduce the dynamic stresses, fracturing, and subsequent breaks in the remaining rock. Most of these methods have been developed in the field, mainly by trial and error. According to Persson et al. (1994), the minimum linear charge concentration required for contour blasting is a function of borehole diameter. Empirically, a good blast is achieved if it is fulfilled that:

$$l = 90\mathrm{D}^2 \tag{4}$$

Where
l: linear charge concentration [kg/m]
D: diameter of blast hole [m]

In tunneling, smooth blasting method is preferable to the pre-splitting, since in the latter, the contour charges are blasted before the rest, more often in separate rounds. The pre-splitting is more expensive than the smooth blasting, since it needs a closer spacing between the contour blast holes, between 50-75% more than for the smooth blasting (see Figure 2.2); moreover, it is often more difficult to fix an extra pre-blasting in the underground excavation cycle (Person et al., 1994).

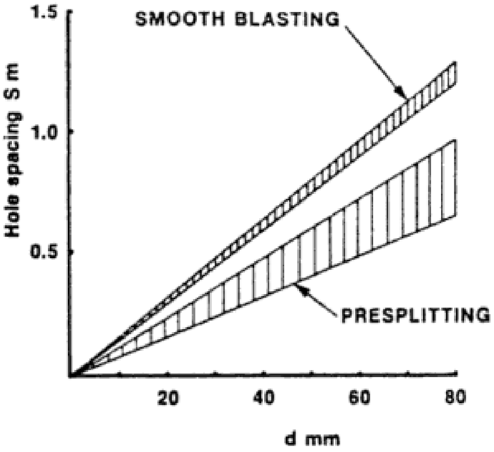


Figure 2.2: Recommended ranges of hole spacing as a function of hole diameter for smooth blasting and presplitting (Person et al., 1994)

In smooth blasting method, geometrically, the row of boreholes adjacent to the planned contour is usually punctured with a spacing/burden ratio of 0.8 and with little delay between blast holes. Furthermore, the use of decoupled charges is considered. According to Saffy (1961) the fact of using decoupled charges generates losses in the shock energy delivered to the rock mass, with which the damage around the blast hole can be restricted.

Conclusions of the literature review

As noted in the literature review, simulation techniques can be used as a support tool in decision-making for mine development planning because they can capture the inherent variability of the mining processes and include this variability in short-, medium- and long-term plans. Most of the models reviewed perform simulations of tunnels with single faces, which may be due to the complexity that modeling of multiple face environments represents. Those models that do consider multiple faces do not consider operational interferences, which cause interruptions in the timing of underground excavation cycles. However, in one case in which interference has been incorporated, the model is conceptual and is not calibrated with respect to real mines.

Regarding SimMine software, it can be said that it has the potential to be used in the mining planning process to evaluate different scenarios before realizing them on field, selecting the most suitable fleet for production targets, identifying bottlenecks with regarding the pieces of equipment and faces working simultaneously, and support the decision making of the planners.

Finally, one of the most important aspects to individually improve the unit operations involved in the construction of tunnels by drilling and blasting, is the selection of the explosive. The use of emulsion in competent rocks is reasonable, given its high brisance and its higher shock energy than gas energy. The emulsion reaches its maximum VOD at critical diameters smaller than those that can be implemented with ANFO. The fact that the emulsion presents a VOD greater than the ANFO, implies a greater brisance on the rock, even in small diameters. The above could mean a lower drilling requirement to achieve the same advance, which in turn means fewer blast holes and therefore less drilling activity time. Furthermore, due to its chemical composition, all explosive emulsions produce less toxic gases volume than the ANFO, which is expected a reduction in ventilation time.

The challenges of this research are aimed at understanding Caving's mine development processes and particularly the excavation of horizontal developments, from a general and a specific point of view. The general point of view consider the planning incorporating the inherent variability of the unit operations and interferences in the development stage, and the specific one consider the individual unit operations, evaluating the blasting.

Chapter 3

Paper I. Simulation of horizontal development in multiple faces considering interferences

Abstract

In Block/Panel Caving mines, the planning and execution of the horizontal developments, usually suffer delays (and therefore, delays in the start of the production) due to the high number of active faces as well as resources and activities to be scheduled simultaneously. In this study, discrete event simulation techniques were used in the development planning phase to assess mining monthly plans of horizontal developments on multiple faces, as an alternative to the conventional planning methods with spreadsheets and average values of historical data. A case study is presented of the Esmeralda mine, belonging to the División El Teniente. This study is based on a previously performed "study of times" in the field, where the main inputs obtained were the time of each unit operation and time of interferences. These times were analyzed statically and represented by triangular probability distribution. A model simulation was constructed and calibrated to estimate the advance of horizontal developments in the short-term. It can be seen from the simulation results that the variability of the processes and the different interferences significantly affect the underground excavation cycle, and their incorporation in the development planning phase could reduce the bias between planned and executed horizontal development advance rates.

Introduction

División El Teniente (DET) is a mine complex located in the General Bernardo O´Higgins Region, in central Chile. The current production is 140,000 tpd, from different sector/mines in production: Esmeralda, Diablo Regimiento, Dacita, Reservas Norte, Pipa Norte, Teniente IV Sur and others (see Figure 3.1). The Esmeralda mine is one of the most important productive sectors of DET. This sector is mined by conventional Panel Caving and reaches a production rate close to 33,000 tpd, which corresponds to 23% of daily production of DET. To achieve this production rate, an area of more than 20,000 m^2 must be incorporated annually. This area is equivalent to the construction of 1,300 m of vertical development, 90 draw points, 10 ore passes and more than 6,500 m of horizontal development (Toro et al., 2016).

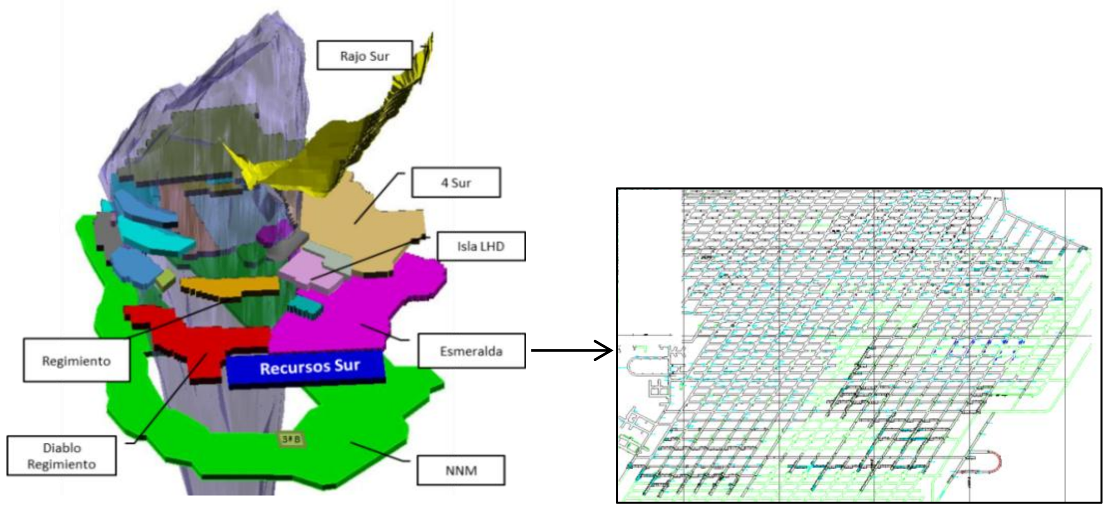


Figure 3.1: Productive sectors of División El Teniente & Production level of the Esmeralda mine (images obtained from División El Teniente –CODELCO-)

The largest amount of horizontal developments is concentrated in the production level. In 2015, a total of 3,821 m was developed at this level (GOBM, 2015; Ccatamayo, 2017). The layout design in production level consists of parallel drifts –haulage drift– separated by 30 m, intersected by a set of galleries –production drifts– separated by 17 m or 20 m and at a 60° angle. The construction of these drifts is carried out through a conventional underground excavation cycle, consisting of eight-unit operations: drilling, charging of explosives (with ANFO), blasting and ventilation, mucking -executed by LHDs from faces to ore pass or stock sites (when there is no availability of ore pass) and then re-mucking-, bolting, meshing and shotcreting. Before the drilling activity, the installation of a mesh on the front of the workface is included. Once the drilling is completed, the mesh is removed, and the explosives are charged; this extra activity is conducted to protect workers from possible rock falls.

Mining Development in División El Teniente

The mining development in DET includes the execution of different processes, which can be divided into three groups: horizontal and vertical developments, civil works and infrastructure assembly (Camhi, 2012). In particular, according to Toro et al. (2016), horizontal developments are of special importance because they represent around 20% of the budget for mining development. Horizontal developments technically correspond to the construction tunnels, which will enable the incorporation of the rest of the mining development works; i.e., the delay in the execution of the horizontal developments will delay the start of civil works and the assembly of the infrastructure. Considering that the horizontal developments constructed by the conventional excavation method are a cyclic and interdependent process, the delay of a single operation, will delay the start of the next one and in general will delay the execution of the whole constructed process.

Particularly in DET, according to Díaz & Morales (2008) between 2000 and 2004, mining development reached an average of 70% compliance in the plans. Between 2005 and 2015, the compliance improved, reaching average values of 92% (Alvarado et al., 2016). The increase in the compliance, according to Bustos (2015), is due to the outsourcing of the mining development works; however, the interference between the contractors and the operation (DET) may be one of the reasons for which 100% compliance has not been achieved.

Ccatamayo (2017) quantified the operating losses (see Table 3.1) produced by interferences in the excavation cycle on the production level of the Mina Esmeralda. The main interferences found were: availability of ore passes, interruption due to the passage of people or equipment, lack of materials, lack of workers, lack of energy and air pressure, equipment downtime, overbreak and presence of water on the work face.

Table 3.1: Time lost by operational interferences (Ccatamayo, 2017)

Unit operation	Drilling	Mucking	Bolting	Meshing	Hilteo*	Shotcreting
Average lost operational [%]	17.9	24.1	13.7	15.5	16.1	17.9

*Hilteo is the activity of install reinforcement bolts (Hilti type) between the mesh and the walls of excavation.

As can be seen in Table 3.1, in most unit operations a significant percentage of time is lost due to interference. These losses represent an additional delta of the time spent by each activity, so it takes longer to complete. As in the excavation cycle, each activity depends on the previous one, the delay of a unit operation will create a domino effect in the cycle, delaying it completely. This is one of the causes of the breaches in the goals of advance, since in some cases, the operational interferences are not incorporated in the planning, even if they are identified, based on what will be corrected for the next period (which is not always it is done, and the delays continue). In other cases, the interferences are identified but not quantified, so when they are included, the plans can be pessimist a lot or, on the contrary, they can be very optimistic.

Discrete event simulation in Mining development

Currently, discrete event simulation is a widely accepted support tool for making decisions in the planning of mining development. Some recent studies, which have included this technique in the planning of horizontal developments are: Vargas et al. (2013) whose research, described planning methodology based on the Monte Carlo method as being much better approximated to the real progress achieved by a tunnel than the conventional methodology, because operating through probability distributions incorporates the variability inherent to the planning processes. Salama (2014) combined discrete event simulation and Mixed Integer Programming (MIP), to evaluate different haulage systems in underground mining, including diesel and electric trucks, shafts and conveyor belts. Botin et al. (2015) proposed a tool that combines discrete event simulation and Program Evaluation Review Technique (PERT) in order to optimize the size and performance of the fleet for the construction of horizontal developments at the Chuquicamata mine; the optimum fleet was determined as the point of economic equilibrium between the additional capital expenditure required to purchase new equipment and the NPV increase resulting from the anticipation of the start-up date which may be achieved. Contreras (2016) conducted a simulation of horizontal developments using Promodel software, which consisted of making a layout composed of 4 parallel drifts joined by a main header and adding interferences. The interferences assumed were: route interruption (temporary closure of any drift), transfer of workers, availability of services, fuel supply, scheduled maintenance, failures and learning curve. Although not all the variables that truly occur in underground mining are considered, the study provided a useful conceptual model to compare scenarios and quantify the impact of the interferences individually on the system. Toro et al. (2016) proposed a conceptual optimization model that makes it possible to generate schedules of horizontal developments automatically. The input of the model were the faces that had to be developed, the number of cycles that could be completed on each of the faces, the typical advance per round, the average times of the activities, and finally the equipment assigned by activity. The output was a Gantt chart of the development schedules, containing the activities of the excavation cycle of each of the faces developed in the program, concluding that the use of the proposed model produces better schedules in terms of maximizing the performance of a fixed fleet of equipment.

These studies demonstrate the importance of simulation techniques as a support tool in planning decisions for mining development and their potential to capture the inherent variability of mining processes and include them in short-, medium- and long-term plans. The models represent good approximations; however, not all of them consider operational interferences, which in many cases limit the excavation cycle.

The offering of software and programming languages for simulations with general and specific purposes, has grown over time. Particularly, in this study SimMine software was chosen. SimMine is a simulator for mining, and has proven to be a very useful tool to represent the behavior of mining processes over time in several underground operations, such as like Oyu Tolgoi and Cadia East.

Methodology

The methodology consisted of an analysis of times (inputs) and construction of the simulation model. The analysis of times is based on the data collection on field carried out by Ccatamayo (2017). The inputs included process times, interference times, shifts and face profile.

Data collection in the field

The aim of the data collection in the field was to measure the time spent to perform each unit operation and identify and quantify the interferences that affect the excavation cycle. The data were collected during six shifts on eight faces operating simultaneously. During the last two shifts, four more faces were being developed; however, they did not reach to complete a full excavation cycle. The data included equipment fleet, cycle times, interferences, work shifts, constructive methodology and face profiles.

1. Unit operations and interferences times

The total time spent to perform each unit operation was measured. This included stop times due to interferences that occurred during the process as well as a quantification of these. The interferences were classified as interferences during unit operations, which are those that occur within the execution time of the activity involved, and as interferences between unit operations, which correspond to non-sequential and non-operative events, represented as the time of inactivity between a unit operation and the next one.

2. Shifts

The contractor company in charge of the horizontal development construction works two shifts per day; contractually the available shift time is 9.6 hours, with 6.3 effective hours of work (Ccatamayo, 2017). There are three blasting schedules: 08:00, 16:00 and 24:00, however, the blasting is almost always done at 08:00, taking advantage of the shift change.

3. Face profile

The following geometry was considered for haulage and production drifts:

Table 3.2: Face profile

	Haulage drift	Production drift
Width [m]	4.2	4.1
Height [m]	3.9	3.9

Simulation Model

The model is based on the layout of the production level of the Esmeralda mine (Figure 3.2). The haulage and production drifts are simplified on axes in the AutoCAD software, and are subsequently exported to the SimMine software. In the latter, we loaded the inputs and sequenced the developments considering the following restrictions:

- Development progress direction
- Sequential order of the excavation cycle
- Development of a minimum of 24.5 m of haulage drift prior to the construction of the production drifts.

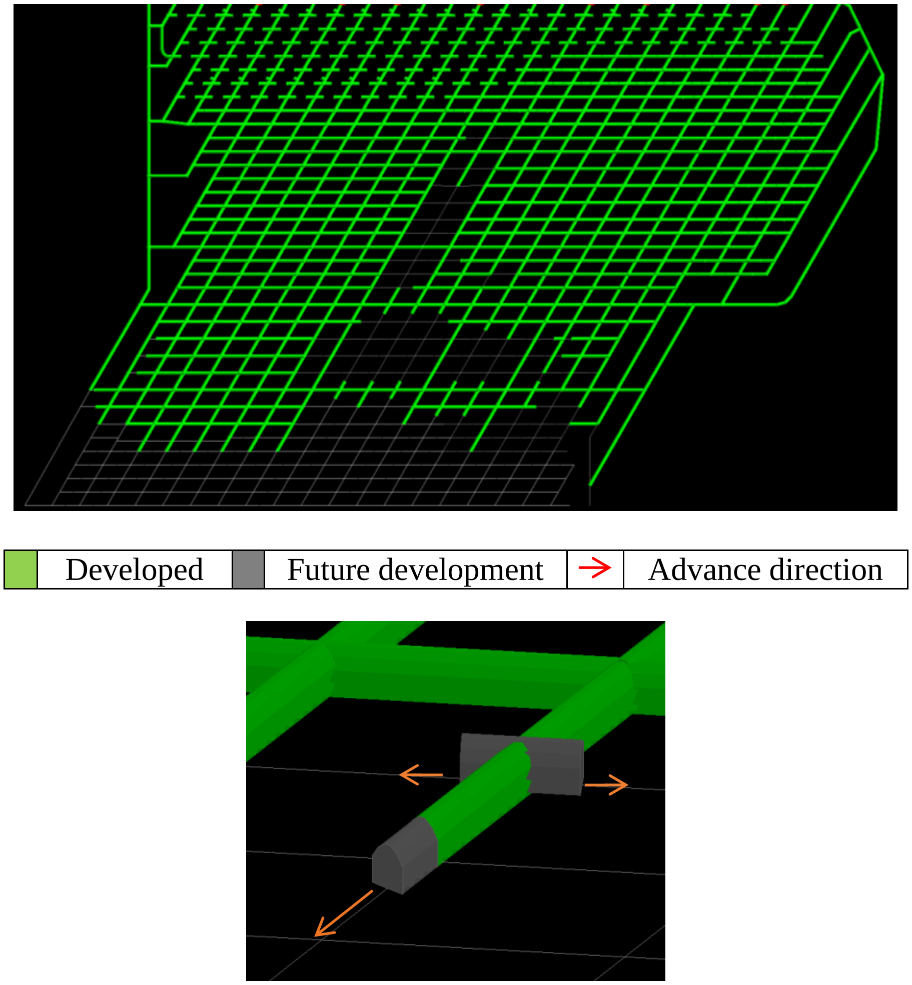


Figure 3.2: Production level layout and advance direction

The influence of interference uncertainty during unit operations is characterized using a triangular probability distribution and implicitly integrated within the time duration of the unit operations. The inactivity times were linked according to the probability of occurrence obtained between unit operations. If there was inactivity, it was assigned a duration time, which followed a triangular probability distribution, which, by generating random numbers, delivered the different times for each event. The sequence of operation is expressed in the flowchart in Figure 3.3.

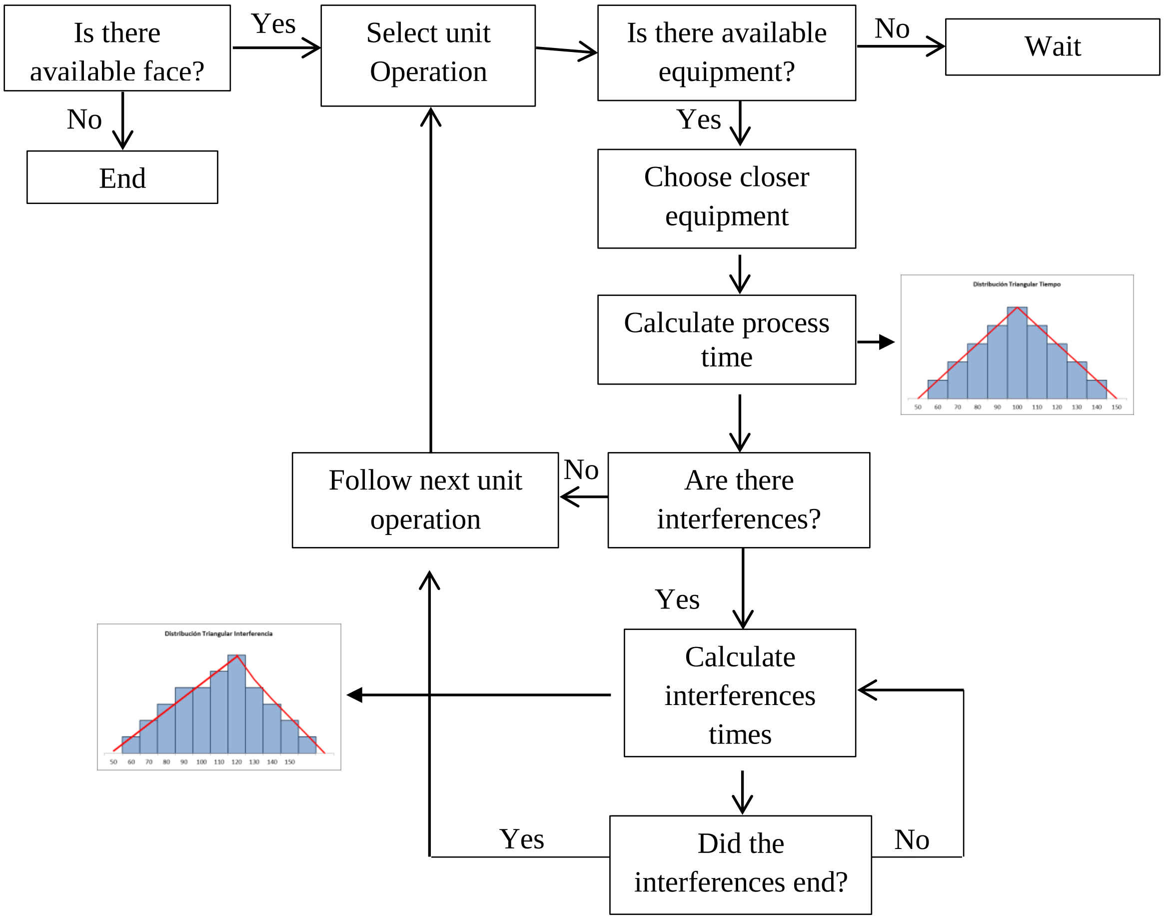


Figure 3.3: Flowchart of simulation model

Results

Data collection in the field

The distribution of the total time at the active faces can be observed in Figure 3.4.

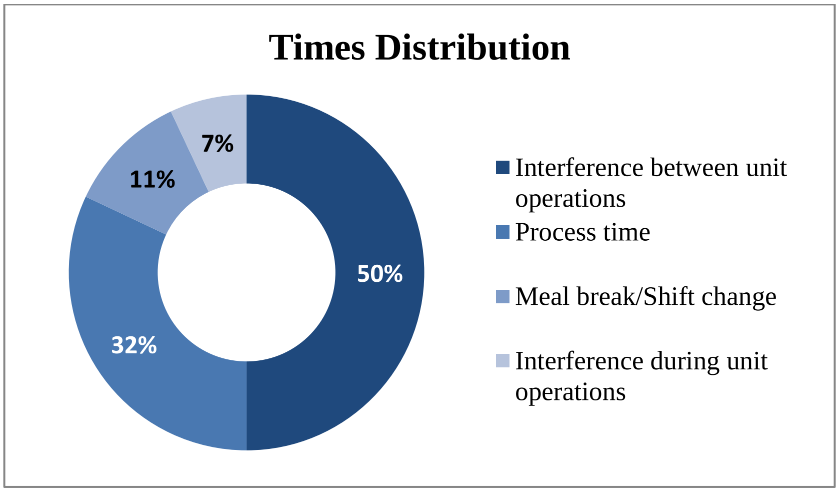


Figure 3.4: Time distribution

Net Time of unit operations

The cycle times were represented following a triangular distribution. Table 3.3 presents the data by activity.

Table 3.3: Unit operations, equipment and net time of processes

Activity	Equipment	Time [minutes]			
		Min	AVG	Mod	Max
Drilling	Jumbo	100	129	100	172
Charging	Mobile Platform	60	85	99	105
Blast and ventilation*	Not Needed				
Mucking**	LHD				
Scaling	Mobile Platform	55	70	-	84
Bolting	Jumbo	104	131	135	184
Grouting	Mobile Platform	82	114	120	128
Meshing	Mobile Platform	78	106	105	125
Hilteo	Mobile Platform	74	104	120	122
Shotcreting	Mixer truck, Roboshot	40	60	45	99

*Blast and ventilation time was fixed at 120 minutes

** Mucking depends on the face location and its distance to the ore pass

Interferences between unit operations

Unit operations at the work faces are not continuous; i.e., between unit operations there is a time lag without activity due to several interferences such as secondary reduction, blasting, seismicity and hydrofracturing, fire simulations, partial or total drift closure, interference with other contractors and CODELCO operations (Ccatamayo, 2017). These interferences significantly affect the excavation cycle, given the high idle time between one unit operation and the next. Figure 3.5 shows the excavation cycle with the interferences between each process, the average duration time (T) and the probability of occurrence (P) of the interferences.

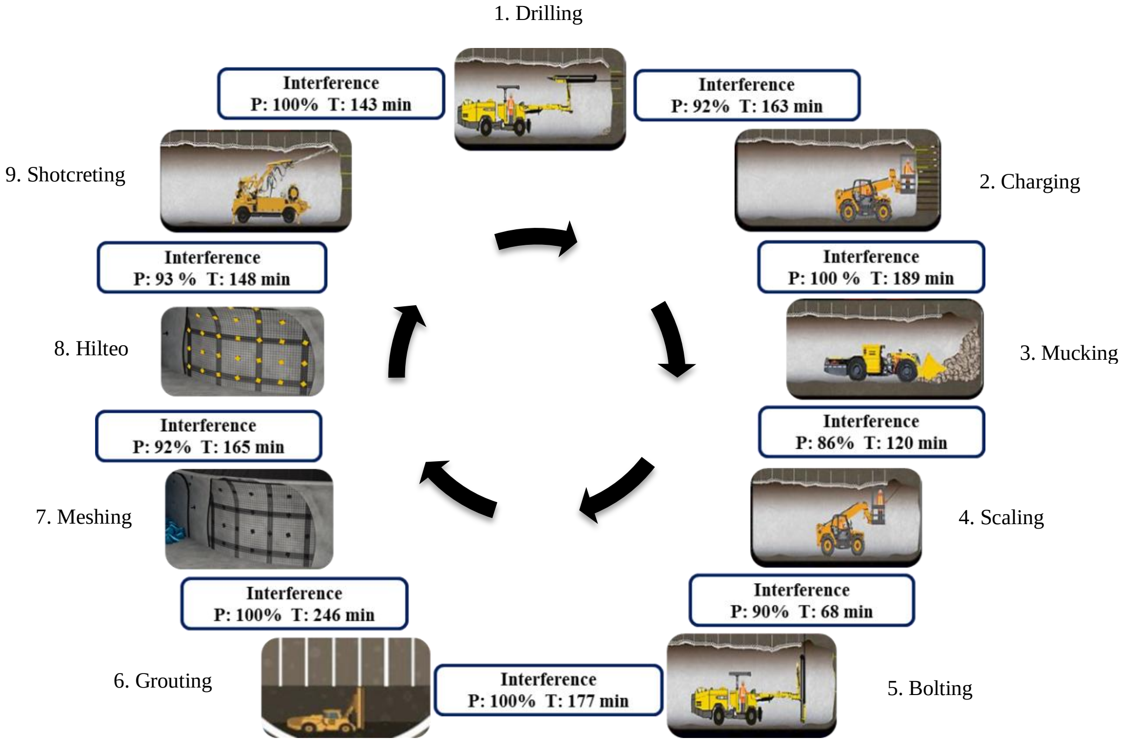


Figure 3.5: Excavation cycle considering interferences

Interferences during unit operations

The total time lost in the execution of one unit operation, because of certain interference, will depend on the frequency with which it occurs and the time it takes until it is solved. In Figure 3.6, the frequency and duration of the interference during unit operations is presented.

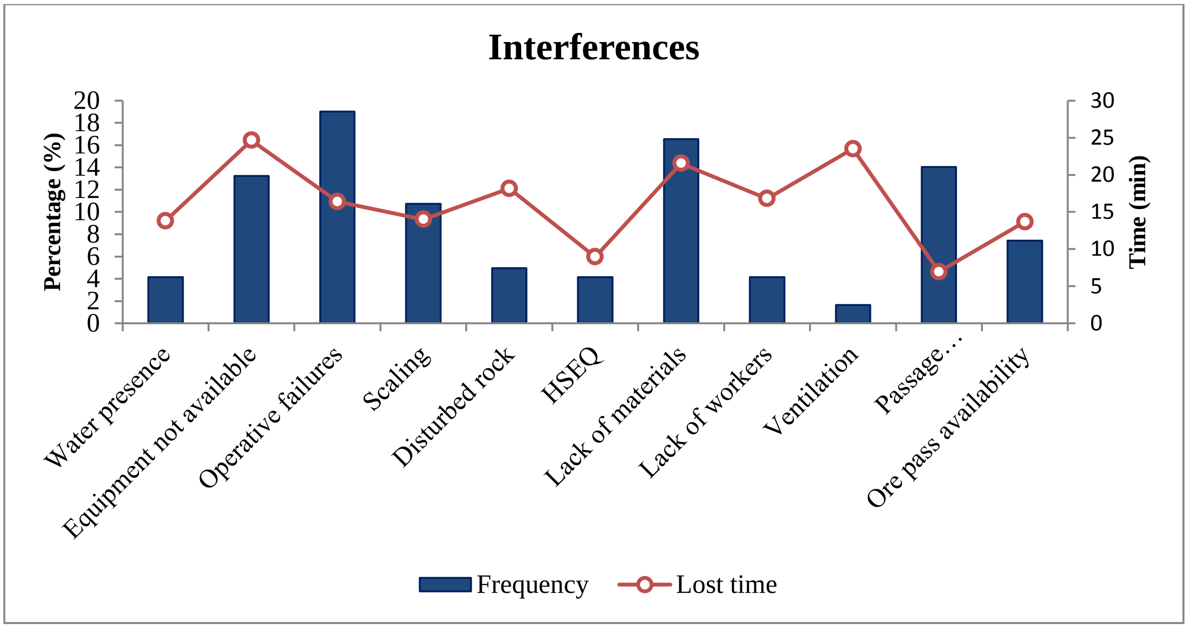


Figure 3.6: Percentage of occurrence and duration time by interferences during unit operations

As can be seen in Figure 3.6, 2% of the interferences were produced by ventilation, although it is the least frequent; each time it occurs, its duration is 24 minutes on average. It may also happen with the interference passage of people/equipment, which occurs with high frequency; however, the average duration of each occurrence is 7 minutes. Cases such as interference due to lack of materials are those that most impact the time of the process, since they are very frequent and their duration per occurrence is high.

The percentage of total time lost in the advance cycle during the study can be seen in Figure 3.7:

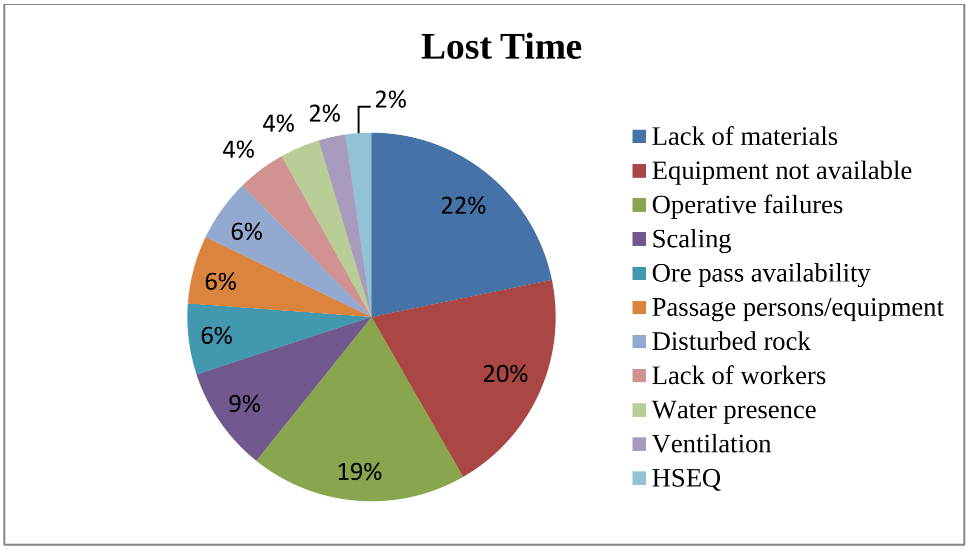


Figure 3.7: Percentage of time lost due to interferences

During the days of data collection, it was noted that the interferences lack of materials and non-availability of equipment had the greatest impact on the duration of the unit operations. As shown in Figure 6, both interferences have a high frequency of occurrence and high duration times per occurrence.

Cycle time

Considering the times involved in the excavation cycle, Table 3.4 summarizes the number of shifts that a face takes to complete an excavation cycle, the time required for unit operations (time in position), the inactivity time within the cycle and the total excavation time by face.

Table 3.4: Shifts, unit operations time, inactivity time and total time of cycle by face

	Shifts	Unit operations time [h]	Inactivity time [h]	Total time of cycle [h]
Face 1	4	18.5	14.3	32.8
Face 2	5	19.0	26.3	45.3
Face 3	4	20.3	17.0	37.3
Face 4	5	19.3	20.5	39.8
Face 5*	5	15.0	23.0	38.0

Face 6	6	20.8	27.3	48.0
Face 7*	5	15.0	20.8	35.8
Face 8	5	19.8	23.0	42.8

*Faces 5 y 7, have no completed cycle.

On average, a cycle takes about 5 ± 1 shifts, with duration of 41 ± 6 hours in total to be completed. The activity time is 20 ± 1 hours on average, and the time in which no activity is performed within the advance cycle is 21 ± 5 hours on average. In other words, the percentage of time that a face is active is 48 ± 6%.

Simulation model

Calibration

Calibration is the iterative process of comparing the model to the real system, making additional adjustments (or even major changes) to the model (Banks et al., 2010). In this case, the total progress reached during 30 days in the mine was contrasted with the model predictions for the same period. In the mine, there are averages of eight active faces per day, which are distributed at the production level following the direction of progress. The face that will be worked is the decision of the shift foreman, depending on the day-to-day situations, so in the model the available faces were randomly chosen at start of simulation and the resources (equipment) were assigned according to the distance between available. In other words, faces located at random were developed, maintaining the direction of progress, the activity sequence of the excavation cycle and the equipment was assigned to the face that represents the travel distance as little as possible. Fifty simulations were run; the advance performance was 317 ± 9 m per month, comparable to the 316 m obtained by the mine in the same period. The graph in Figure 3.8 compares the average of the fifty simulations and the real advance, indicating a reasonable trend between the real and simulated advance.

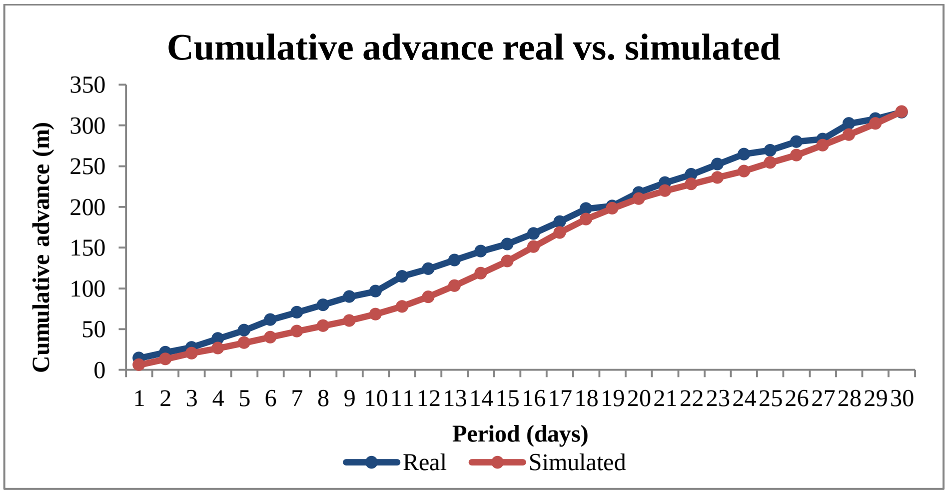
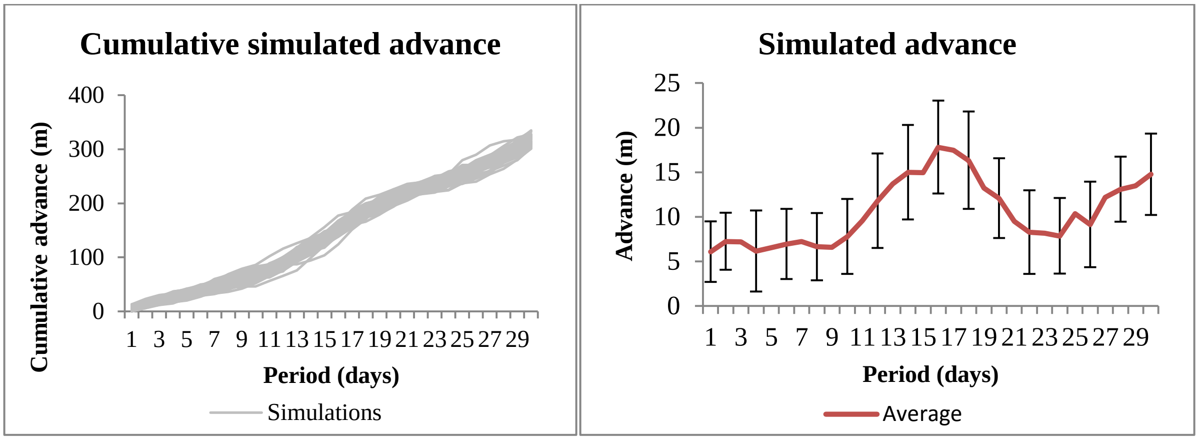


Figure 3.8: Cumulative advance real vs. simulated

Advance Performance

The performance rate was an output of the model used to contrast the planned advance, the real advance and the simulated advance. For this, the information of the same month in which the data were collected was used. Figure 9 shows the progress (cumulative and daily) of the horizontal developments achieved by the simulation model during the 30-day period.



(a) **(b)**

Figure 3.9: Simulated advance considering interferences (a) cumulative (b) daily

Table 3.5: Summary of planned, real and simulated advance rate

	Period [days]	Advance [m]	Advance rate [m/day]	Difference [%]
Planed	30	271	9	14.3
Real	30	316.2	10.5	
Simulated	30	317.0 ± 8.9	10.6 ± 0.3	0.3 ± 2.8

As observed in Table 3.5, the average of the simulations was 317 ± 9 m, which is closer to the real advance of 316 m, than what was planned in a conventional way (271 m). This difference is significant because the error in the planning of the progress goals can be reduced if the variability in the unit operations is incorporated in addition to the interferences present in the mining development.

Simulation without interferences

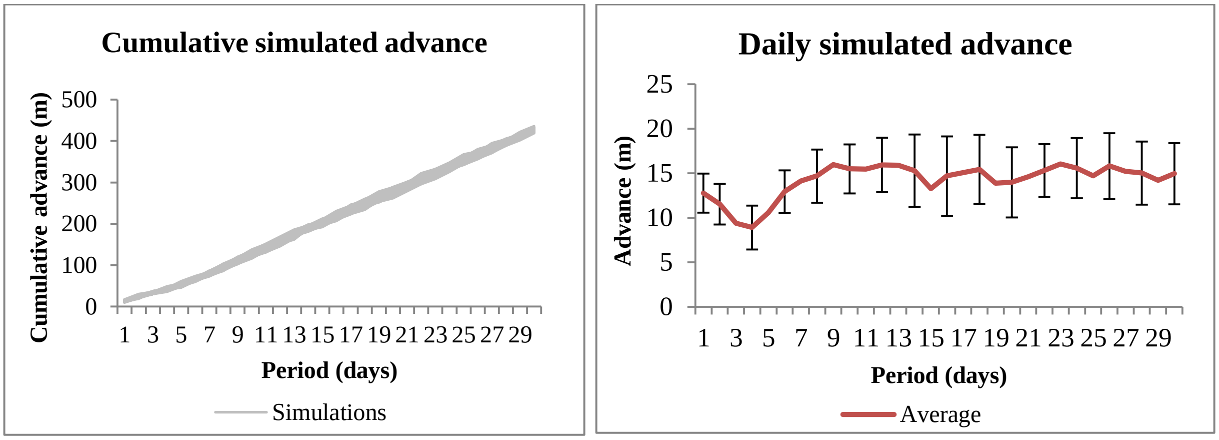
Once the simulation model with interference is established, the behavior of the progress of horizontal developments can be observed when only the net time of each of the activities of the cycle is considered; i.e., without the time delta present for interferences during unit operations. An increase in the monthly advance is expected; however, this cannot be assumed linearly, due to the development is not being carried out on a single face, but on multiple faces, and additionally because the blasting takes place at a specific hour, for which, although there is a reduction in the time of unit operations, the face must wait until the time scheduled to execute the blast. And this must be so, since every time it is blasted, insulation occurs, which greatly interferes in the mining process.

When simulating for a period of 30 days, without interference during unit operations, an average advance of 323.3 ± 8.7 m was reached, which indicates an increase of 2.3 ± 2.8% over the real one. On the other hand, according to the study time in the field, it was noted that the development of faces is significantly affected by interferences (due to inactivity) between unit operations. Since these were not quantified individually, there is no certainty about the percentage of incidence of each; however, if it is assumed that these random activities do not intervene in the cycle, a greater occupation of the work face could be expected, as could an increase in the monthly advance. Simulating the development in multiple faces, without interferences between unit operations, the advance would be 426.9 ± 3.9 m on average, which indicates an increase of 35.0 ± 1.2% over the real one. These simulations consider the interference during unit operations.

In Table 3.6, the summary of the planned, real and simulated advance with interference and simulated without interference for a period of 30 days is shown. In the graphs in Figures 3.10 and 3.11, the progress performance (accumulated and daily) of the horizontal developments obtained by the simulation models without interference is shown.

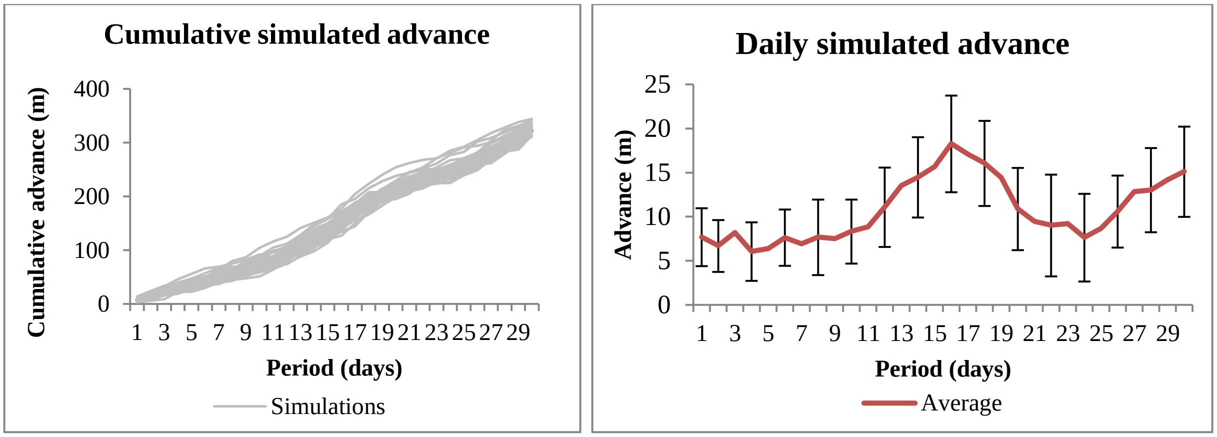
Table 3.6: Summary of advance rate and increase of planned, real and simulated advances with and without interferences

	Advance [m]	Advance rate [m/day]	Increase [%]
Planed	271	9	
Real	316.2	10.5	
Simulated	317.0 ± 8.9	10.6 ± 0.3	
Simulated without interferences during unit operations	323.3 ± 8.7	10.8 ± 0.3	2.2 ± 2.8
Simulated without interferences between unit operations	426.9 ± 3.9	14.2 ± 0.1	35.0 ± 1.2



(a) (b)

Figure 3.10: Advance simulated without interferences during unit operations (a) cumulated (b) daily



(a) **(b)**

Figure 3.11: Advance simulated without interferences between unit operations a) cumulated b) daily

As the input values are more limited, the results are also smaller. In the last simulation where variability due to interferences between unit operations was eliminated, leaving only the variability of the process times, the standard deviation was 3.9 m, whereas in the previous ones it was 8.9 and 8.7 m. The use of the real and simulated front is summarized in Table 7.

Table 3.7: Time of unit operations, activity time, inactivity time and percentage of face utilization

	Unit operations Time [h]	Inactivity time [h]	Total time of cycle [h]	Face Utilization [%]
Real	19.6	21.4	41.0	48.4
Simulated	19.0	21.3	40.3	49.1
Simulated without interferences during unit operations	17.5	20.8	38.4	51.5
Simulated without interferences between unit operations	19.1	11.1	30.2	65.6

The percentage of face utilization represents the time in which the unit operations of the excavation cycle are carried out; note that, as the time of interference decreases, the face utilization is greater. The simulation without interference between unit operations showed a utilization of 65.6%. The remaining percentage of inactivity (35.4%) corresponds to the percentage of time that a face waits while the equipment arrives to operate. Given the amount of equipment vs. active faces, and their location of them, the passage of equipment from one face to another occupies a significant amount of time in the cycle. A possible alternative solution to this could be to divide the mine into sectors with a specific fleet of equipment, so that the traffic time is reduced.

Conclusions

From the study time in the field, it is concluded that, on average, 50% of the shift-by-face time corresponds to interferences between unit operations, 36% to the net time of the unit operations, 11% to shift change and meal break, and the remaining 7% to interference during unit operations.

The use of discrete event simulation tools makes it possible to incorporate variability in the times of processes, interferences, restrictions, etc. into the mine development, demonstrating that such a tool has the ability to capture and model the uncertainties inherent to the construction of tunnels, unlike the traditional methodology, which uses historical data and average values for its predictions.

The simulation model with interferences reasonably represents the real behavior of the horizontal developments in the mine. The average advance of the simulations was 317.0 ± 8.9 m, and the planned was 271 m, with the average results of the model with interference being closer to the real than the planned.

To generate an increase in the advance it is necessary to consider the reduction of excavation cycle time, which can be achieved by optimizing the processes involved and reducing interference time. Considering this last issue, the increase in the progress was evaluated, since from the study time in the field, the strong influence of the interferences on the forward performance of the horizontal developments was evidenced.

The simulation without interference during unit operations showed an increase of 2.2% in the monthly advance and a face utilization of 51.5%. Although the increase is not high, because the impact of the interference associated with unit operations is 7% of the global time of the excavation cycle; identifying and quantifying interferences allows them to be incorporated into development plans and, more importantly, to be reduced.

The simulation without interferences between unit operations resulted in an increase of 35.0% in the monthly advance and a face utilization of 65.6%. The remaining percentage that the face is inactive corresponds to the waiting time while the equipment arrives to operate. Although the simulation showed positive results, the impact could not be established separately from the interferences between unit operations such as blasting, seismicity and hydrofracturing, fire simulations, partial or total drift closures, interaction with other contractors and CODELCO operations. Therefore, it would be important to do a study and time analysis (similar to the one performed for interference during unit operations), taking into account the strong impact they have on the excavation cycle.

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Chapter 4

Paper II. A Comparison of Emulsions and ANFO usage in the Horizontal Development Process at El Teniente

Abstract

El Teniente is among the largest underground mines in the world with production of approximately 135,000 tons of copper per day (Baez, 2016). After 112 years of operation, mining is conducted in deeper and more competent rock mass conditions than when the mine was initially opened. The high production rates also require developing a larger number of tunnels in a more efficient way (rapid advance rates at a low cost). For these reasons, El Teniente has defined mine development as a key strategy area for its future, and as such it is continuously looking for technological opportunities to improve safety, efficiency and costs. For many years, ANFO has been the explosive used in this operation. In the last year, emulsions have been extensively tested at El Teniente in horizontal developments to technically quantify their benefits. Trial tests were initially conducted in the Diablo Regimiento sector followed by industrial application in the Pacífico Superior sector. Results show that emulsions have many advantages including a smaller volume of poisonous gases and, therefore, less ventilation time required, and fewer boreholes and greater efficiency in terms of advance per round when compared to ANFO. In this article the fundamentals and statistical analysis of the results derived from field tests at El Teniente are presented and compared.

Introduction

El Teniente (DET) is a mine located in the Libertador General Bernardo O´Higgins Region, 50 km from Rancagua, Chile, at a height of 2500 m. Its copper deposit, mined by the Block Caving method, has one of the highest production rates in the world.

Today the extraction and development at El Teniente occurs in what is locally termed “primary ore” under high stress conditions. The main characteristic of primary ore rock is its high hardness and brittleness. On the other hand, the high production has also meant high mine preparation rate requirements to maintain production capacity given the geotechnical conditions at the mine. This has led to the adoption of a strategic plan for mine development for its present and future (Díaz, 2008). One the strategic focuses have been a review of mining practices including technological and lean management.

In terms of the technologies, one focus has been an operational review of explosives. For many years, ANFO has been the explosive used at the mine due to its low cost and familiarity of use by the operators. However, there are other types of explosives such as emulsions that have been on the market for many years. Emulsions are a liquid salt solution made of small droplets, with each droplet surrounded by a thin oil film. ANFO is a mixture of crystalline or prilled ammonium nitrate (AN) and fuel oil (FO). The emulsion properties make it viable for use in hard rock and help to obtain efficient blasting. The literature contains criteria for defining the explosive given its characteristics for a given rock mass condition for horizontal developments to achieve a given level of performance, but hard data is not available.

Literature review

Explosive-Rock relation

Rocks could be mechanically classified as having elastic or plastic behavior. Elastic rocks are those having relatively higher compressive strength, while plastic acting rocks are those having lower compressive strength (Grant, 1970; Bhandari, 1997). The ease of generating new fractures in the medium is a function of the strength properties of the rock material. For example, with hard rock which is more elastic, a high brisance explosive is recommended (Brady & Brown, 2004).

Velocity of detonation

To obtain good blasting performance, especially good fragmentation, the choice of a particular type of explosive must consider important aspects such as velocity of detonation (VOD) of the explosive and the P-wave velocity of rock. The VOD is proportional to the detonation energy released by the rock, and if it is increasing, it produces a better stress distribution. The VOD of emulsions is greater than ANFO; it means that emulsions are suitable for hard rock whose P-wave velocity must be equal to or less than the VOD of the explosive. When VOD is less than the P-wave velocity of the rock, the P-wave could compress the explosives and result in detonation failure (Zhang, 2016). The VOD of explosive decreases as the diameter of the charged column decreases (Cooper, 1996).

Water resistance

The water resistance of an explosive defines its ability to detonate after being exposed to water. Emulsion is a liquid salt solution made up of 0.005 mm droplets, and, as noted above, a thin oil film surrounds each droplet. It is this oil film that encloses the drops of salt solution and gives the emulsion its outstanding resistance to water (Johansson, 2000). A major disadvantage and limitation of ANFO is its lack of water resistance. Ammonium nitrate dissolves easily in water even with the added fuel oil. ANFO containing more than about 10% water will fail to detonate (Hustrulid, 1999).

Advance

Advance per blast is affected by multiple factors including: the properties of the rock mass, geological considerations, blast design, drilling accuracy, explosive selection, the initiation system, the timing of the round, and the use of effective stemming products (Prout, 2010). Underground blasting does not have effective free face, therefore, it is necessary to generate a void to which will be released the adjacent charged boreholes; this first void is called cut. With a hard rock type and parallel cut (four-section cut), according to Persson et al. (1994) the maximum hole depth depends on the empty hole diameter, the larger the diameter, the larger the hole depth that can be achieved. -If the advance achieved is less than 95% of the drilled hole depth, drifting becomes very expensive for the mine.

Overbreak

The factors influencing blast damage can be broadly categorized in three areas: rock mass features -especially discontinuities of which important considerations include orientations, aperture, frequency, filling in the joints, RQD, watery conditions and state of stress-; explosive characteristics and distribution; and blast design and execution (Singh & Xavier, 2005). Regarding the latter two aspects, it was found that the smooth blasting method reduces overbreak. Persson et al. (1994), suggest an empirical relation in which the minimum linear load concentration required for contour blasting is a function of the charged hole diameter. In the smooth blast method the row of holes adjacent to the planned contour is usually drilled with an S/B ratio of 0.8 and with little delay between them (Persson et al., 1994).

Furthermore, if the charge is decoupled, this can generate losses in the shock energy delivered to the rock mass, which can restrict the damage around the borehole. In tunneling, the smooth blasting method is preferable to presplitting, since the latter is more expensive than smooth blasting, as it requires a closer spacing between contour drill charged holes; moreover, it is often more difficult to fix an extra pre-blasting operation in the underground advance cycle (Persson et al. 1994).

In summary, the literature indicates that emulsions present properties that allow efficient blasting in hard rock, given their high VOD and water resistance. However there is a lack of reported tests in the field that could be used to verify all the benefits mentioned above. For this reason full scale trials were conducted at El Teniente using emulsions to quantify and compare the performance of ANFO and emulsions. In this article the results of these experiments are shown.

Experimental site

El Teniente (Figure 4.1) is a large mining complex with several productive mines or sectors located around of a pipe “Pipa Braden” where mineral is located. For this study, two kinds of tests were carried out in two sectors with similar characteristics. To define the baseline of blasting, trial tests were conducted in the Diablo Regimiento (DR) sector follow by industrial application at the Pacífico Superior sector (PS).

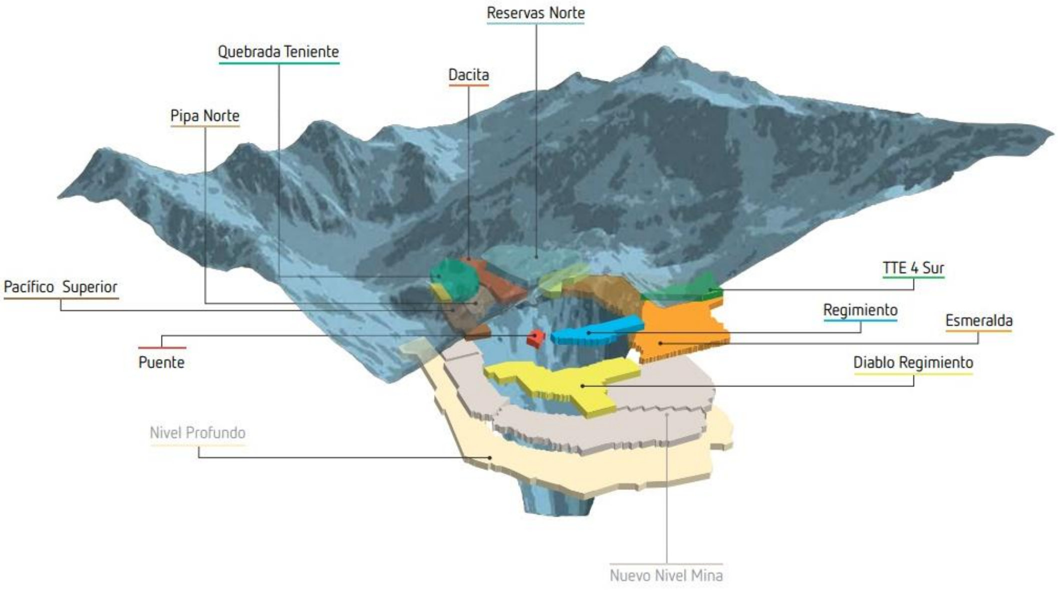


Figure 4.1: Location of sectors at El Teniente mine (CODELCO, 2016).

El Teniente complex is mainly composed of two types of rock: CMET (Complejo Máfico El Teniente), which in turn is composed of Gabbros, Diabases and Basaltic Porphyry, and a Breccia Complex. The rock mechanic characteristics of the rock types for Diablo Regimiento and Pacífico Superior sectors are similar and are shown in Table 4.1. The CMET could be considered as rigid, fragile and hard rock.

Table 4.1: Geotechnical characteristics of El Teniente´s rock mass (CODELCO, 2017)

Rock Type	CMET	Breccia
Percentage of area [%]	80	20
E [GPa]	57 ± 11	27 ± 4
Vp [m/s]	5646 ± 428	4287 ± 260
$\boldsymbol{\sigma_t}$ **[MPa]**	11	7
UCS [MPa]	135 ± 12	73 ± 22

The Diablo Regimiento sector is one of the 15 productive sectors in DET (CODELCO, 2014). This sector is located in the southernmost part of the deposit (Figure 4.1). The stress field in-situ is σ_1 = 41 MPa and σ_3= 25 MPa. The geotechnical characteristics of the rock type where tests were carried out are shown in Table 4.1. In this case blasting tests were conducted in the production and undercut levels, having cross sections of 19.9 m^2 and 16.3 m^2 respectively.

PS (Figure) is located at the west of Pipa Braden between the Diablo Regimiento and the Pipa Norte sectors (CODELCO, 2017). This sector has historically been affected by water inflow with values reaching 105 ± 137 l/sec (CODELCO, 2016). As shown in Figure 4.2, this sector has 80%

of CMET rock type and 20% of Breccia rock. Geotechnical characteristics are shown in Table 4.1.

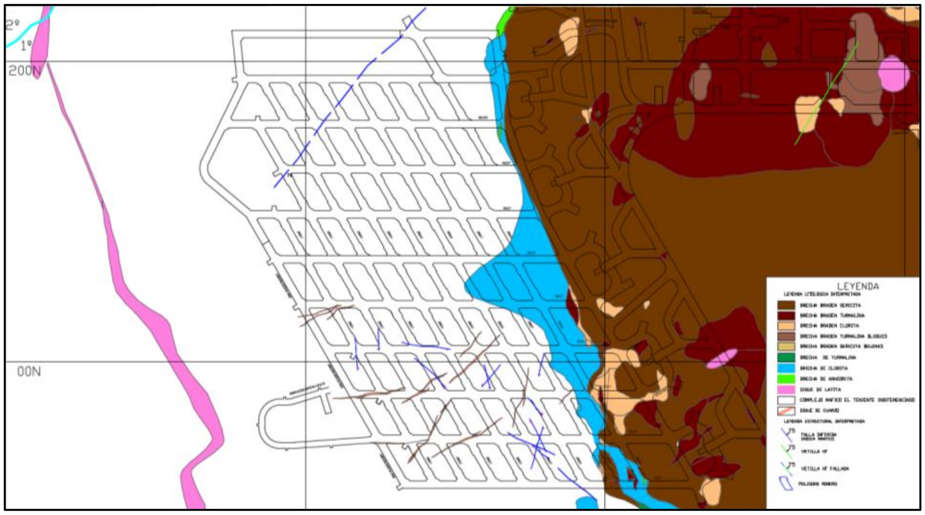


Figure 4.2: Rock types in the Production Level of Pacífico Superior Sector (Codelco, 2017)

Trial Tests at Diablo Regimiento

The performance of ANFO and emulsion explosives was initially evaluated in two periods: from 20-07-2016 to 23-08-2016 test using ANFO and from 23-11-2016 to 18-01-2017 test using emulsions. The results from these tests define the baseline over which industrial tests were later conducted. During the trial tests, drill length, linear advance length and overbreak were measured. Based on these variables, the following parameters were calculated to assess the explosives' performance:

1. **Effective advance**

Is the ratio between the linear advance length in meters after blast and the drilled length. The information about linear advance length is stored by the operators in a common database known as the *Collaborator Platform*.

2. **Contour Damage Quantification**

Is reported as the percentage of overbreak. It was obtained by the processing of photography after the blast using ADAM technology and the information received by the *Collaborator Platform*. The processing of photography converts them in a 3D map, through which geological and geometric information of tunnel is extracted.

Table 4.2 presents a summary of the main results using ANFO and emulsions. For the first explosive, the average of effective advance reached 87% and the percentage of overbreak reached 24% on average. For the emulsions, the effective advance reached 94% and the percentage of overbreak was 7.4% on average.

Table 4.2: Blasting trial test results using ANFO and emulsions at DR

Level	Data [un]	Explosive	Hole depth [m]	Advance length [m]	Effective advance [%]	Overbreak [%]
Undercut	5	ANFO	3.8	3.31	87.4	23.0
Production	1	ANFO	3.8	3.26	86.0	25.2
Production	5	Emulsion	3.6	3.4	93.6	7.4

During the trials, the velocity of detonation (VOD) was also measured for each explosive. In the case of ANFO, the VOD had values of 3602 m/s and 3517 m/s, in a hole diameter of 45 mm. In the case of emulsions, the VOD values reported were between 4162 m/s and 4058 m/s measured in a hole diameter of 45 mm. Therefore the VOD increased 15% when emulsions were used. Finally, the results obtained show there was an opportunity for improvement in blasting performance by using emulsions as an explosive. However the amount of data was not sufficient and more blasts were executed in an industrial application.

Industrial Tests at Pacífico Superior

The blasting tests were carried out from February to June 2017. Blasting tests were conducted through the CMET rock type at production level in haulage and production drifts with cross sections of 22.9 and 17.9 m^2 respectively. The explosives were Emulsions, a Subtek^{TM} Charge (Orica, Chile), and ANFO, and both types were initiated by a pyrotechnic detonator. The database for analysis is composed of 110 advance blasts with emulsions and 36 using ANFO.

During the blast tests, gas dilution, effective advance and overbreak variables were measured. The measurement mechanism is described below:

1. **Ventilation time**

This is quantified in terms of the ventilation time required to achieve proper air conditions for the production and undercut levels. Thirty minutes after blasting and according to Chilean standards and regulations, mine personnel enter the blasted area and measure the gas concentrations of CO and NO_2 with a gas meter. If these concentrations are above the legal limit value, miners are not authorized to enter. After an elapsed time, mine personnel repeat the process until the poisonous gas concentration is below the legal threshold limit values. Percentage values of concentration of toxic fumes are recorded in the shift's gases control log.

2. **Effective advance**

This is calculated as the ratio between the actual drift advances divided by the drilling length. The actual drift advance is calculated using topographic measurement after the mucking and supporting activities are conducted, using Total Station Equipment (TES). To calculate the drift advance per round, two measurements of the distance were considered (Figure 4.3).

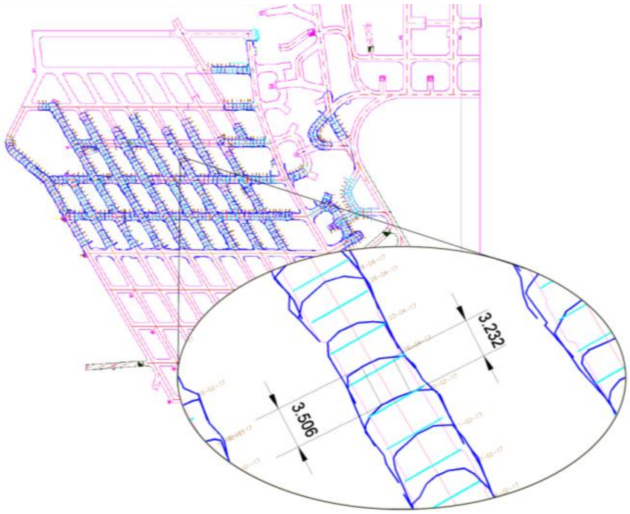


Figure 4.3: Measurements of the advance on plan view

3. Contour damage

This is calculated as the percentage of overbreak. As in the case of the advance per ring, the excavation perimeter to estimate the real cross section was calculated using the TSE measurements. Overbreak is the difference between the real cross section and designed cross section area. Figure 4.4 shows a cross section where the real and designed area for a drift can be observed. This value was reported in percentage terms using the following calculation:

$$Overbreak\ (\%) = \frac{Real\ cross\ section - Designed\ cross\ section}{Designed\ cross\ section}$$

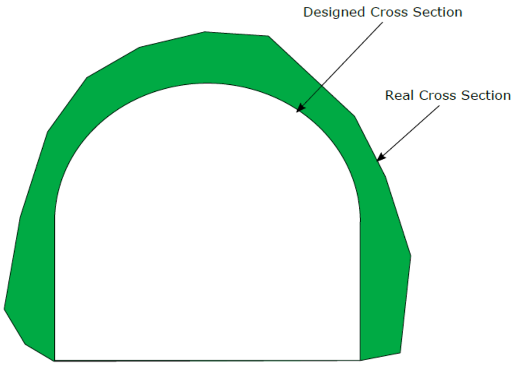


Figure 4.4: Example of designed and real cross section for an underground face

Results

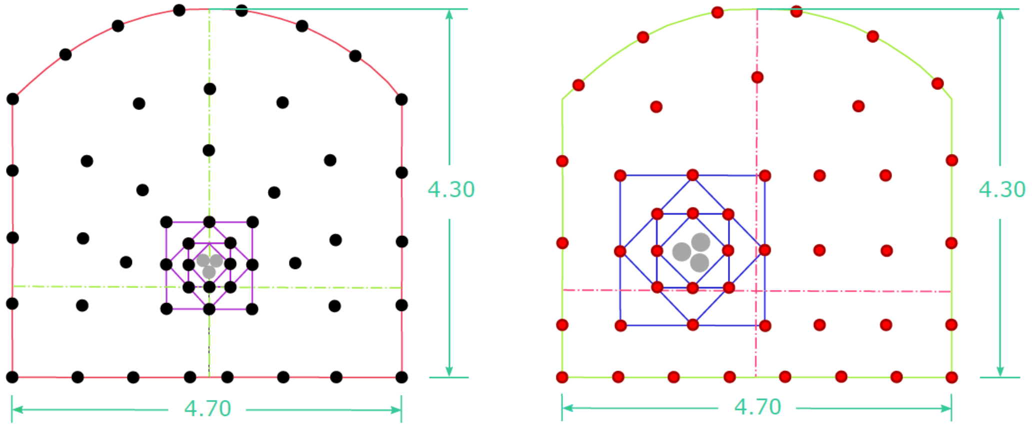
Drilling Pattern

The blasting design at the mine depends on the section and explosive type (see Figure 4.5 and 4.6; and Table 4.3). As can be observed, the number of boreholes increases as the section area increases. Also the required number of charged boreholes using emulsions is smaller than for ANFO (13% and 12% less in haulage drift and production drift respectively). A smaller number of boreholes plays an important role in determining the development cycle, i.e. the time required between blasting procedures, as a fewer number of boreholes means savings in time and drilling costs.

Table 4.3: Number of boreholes in production drift and haulage drift for ANFO and emulsion

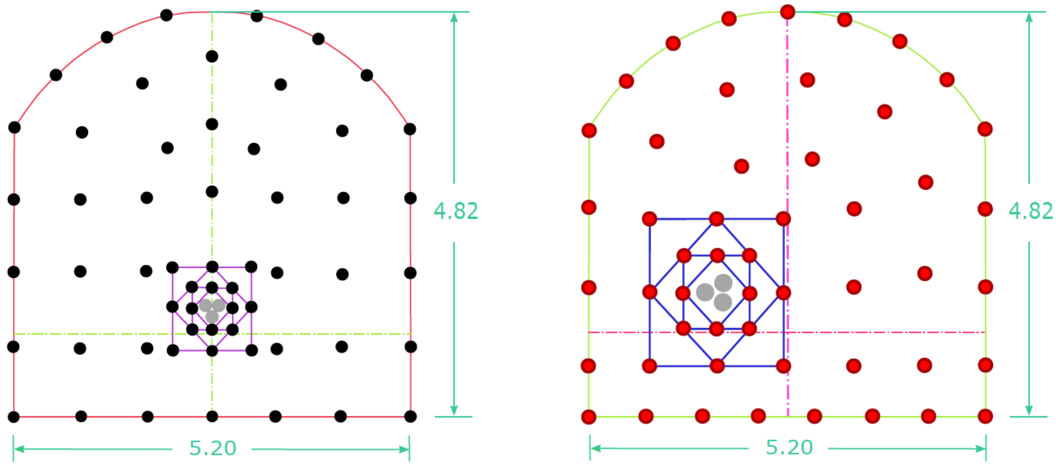
	ANFO			Emulsion		
	Charged Holes [d=45 mm]	Empty Holes [d= 102 mm]	Total Holes	Charged Holes [d=51 mm]	Empty Holes [d=102 mm]	Total Holes
Production Drift [4.3 x 4.7 m]	52	3	55	45	3	48
Haulage Drift [5.2 x 4.82 m]	58	3	61	51	3	54

d= hole diameter



(a) (b)

Figure 4.5 (a) Pattern of Haulage Drift charged with ANFO (b) Pattern of Haulage Drift charged with emulsion



(a) (b)

Figure 4.6 (a) Pattern of Production Drift charged with ANFO (b) Pattern of Production Drift charged with emulsion

Gas Dilution Time

The composition of an explosive is said to be balanced when the oxygen contained in its ingredients combines with the carbon and hydrogen content to form mainly carbon dioxide and water (Bhandari, 1997). Then, the chemical composition of an explosive is one of the most important factors influencing the volume of poisonous gases after the blast. In general terms, emulsions produce less volume of poisonous gases when compared to ANFO and nitroglycerine, especially nitrous gasses (Johansson, 2000).

During the blasting tests at PS, the gas dilution time was the parameter used to indicate which one of the explosives produced the lowest poisonous gas concentration based on the assumption that the ventilation time should be smaller on the faces with lower concentrations. The average ventilation time in faces blasted with emulsions was 43 ± 12 minutes, whereas with ANFO it was 81 ± 99 minutes. Emulsions, then, required 38 minutes less for ventilation purposes, representing a 47% savings in average ventilation time. As noted, the standard deviation in ventilation time for emulsions is smaller than for ANFO indicating also a more predictable behavior. Figure 4.7 shows the ventilation time distribution necessary to dilute the gases post-blast using emulsion and ANFO explosives respectively. In terms of frequency, it shows that with emulsions in 93% of the cases it was possible to enter the blasted areas before 60 minutes. On the contrary in the case of ANFO, in 40% of the cases, entry was not possible until after 60 minutes had passed.

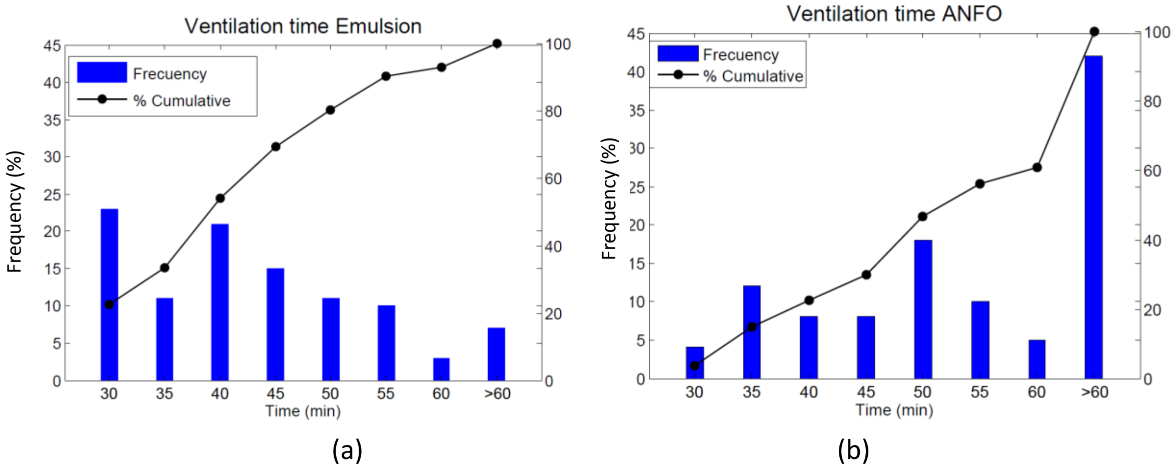


Figure 4.7 (a) Ventilation time with emulsion (b) Ventilation time with ANFO

Overbreak

Overbreak in tunneling is the undesirable break of the rock due to blasting and geomechanics issues. The rock mass where tests were conducted is considered good rock quality, without important joint sets and under a relatively low stress field (σ_1=17 Mpa y σ_3=12 Mpa). From a blasting point of view, blast-induced damage is highly localized around the immediate perimeter of the blasting area (Singh & Xavier, 2005), so that the explosive charge used in perimeter holes highly influences the percentage of overbreak.

During the tests of emulsion at the mine, two different approaches were carried out over two different periods of time. In the first period, from February 7 to May 17, the explosive used in the perimeter holes was the same emulsion (Subtek^{TM} Charge), but its density was reduced to 0.9 g/cm^3 which delivers a linear charge concentration of about 1.8 kg/m. In the second period, from May 18 to June 30, the explosive used in the perimeter holes was packaged dynamite reaching a contour with a linear charge concentration of about 0.3 kg/m. For ANFO, the explosive used in the perimeter holes was packaged dynamite and the main results are shown in Table 4.4 and Figure 4.8.

Table 4.4 Percentage of overbreak with emulsion and ANFO

	Period 1 (February 7 to May 17)		**Period 2 (May 18 to June 30)**	
	Emulsion	**ANFO**	**Emulsion**	**ANFO**
Explosive used in contour	Emulsion of 0.9 g/cm^3	Dynamite	Dynamite	Dynamite
Data [un]	66	21	10	5
Overbreak average [%]	32 ± 17	24 ± 15	15 ± 9	16 ± 8

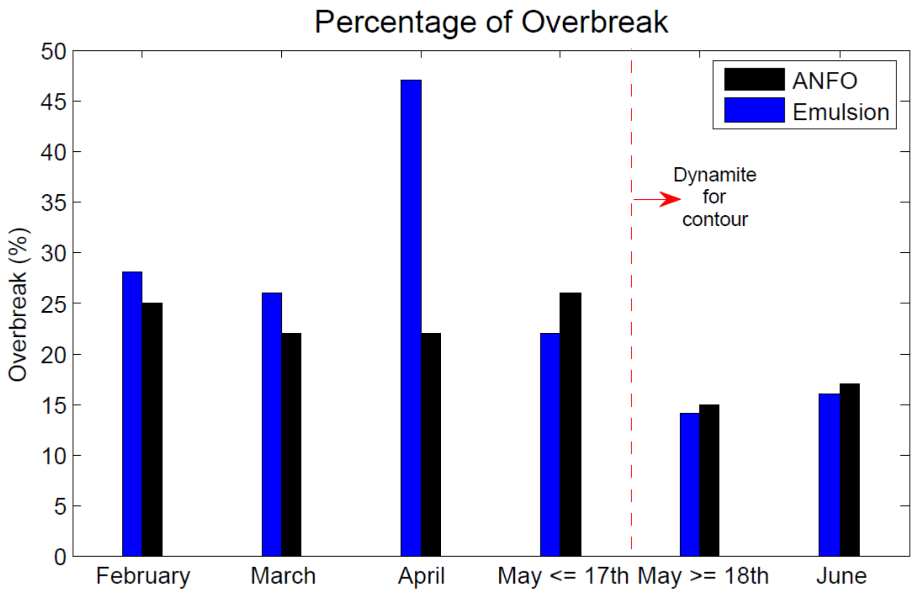


Figure 4.8: Percentage of Overbreak

The percentage of overbreak using emulsions was significantly reduced from 33% (Period 1) to 15% (Period 2). In blasted drifts using ANFO, the percentage of overbreak was reduced from 24% (Period 1) to 16% (Period 2) because of improvement accuracy in the drilling activity. The results suggest that the type of explosive used in the perimeter hole, as the literature indicates, is a key variable in the control of overbreak. Also, the use of decoupled charges in perimeter holes could help to reduce the damage surrounding the hole.

Effective Advance

Effective advance is a parameter that allows the blasting efficiency to be assessed in terms of drilling length. According to Persson et al. (1994), an effective blast should be around 95% to be considered an effective advance.

The average hole depth was measured in the case of emulsions at the front after drilling reached 3.46 ± 0.30 m. As shown in Figure 4.9, hole depth is distributed and shows variability. In the case of ANFO the values of hole depth were not measured. All boreholes, including relief holes, were drilled at the same depth.

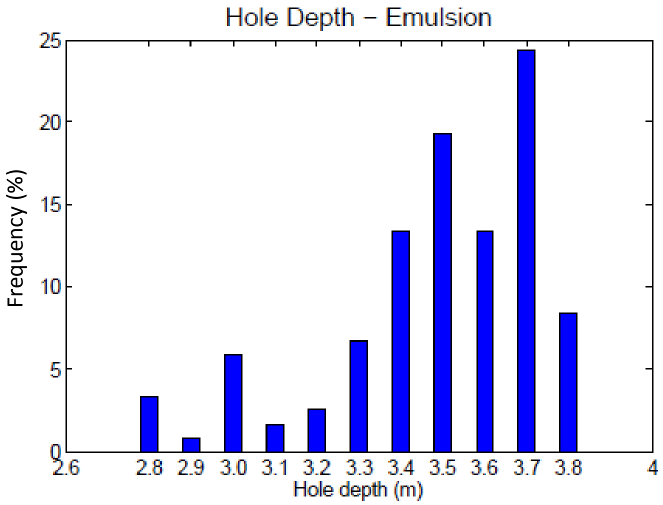


Figure 4.9: Hole depth for Emulsion

Figure 4.10 shows the effective advance between February and June 2017 for emulsion explosive. This indicates that effective advance reaches 96% ± 6% for emulsions. Therefore, emulsions are more effective than ANFO for the study case when compared to the 87% defined at baseline. This improvement corresponds to a 10% increase in blast efficiency.

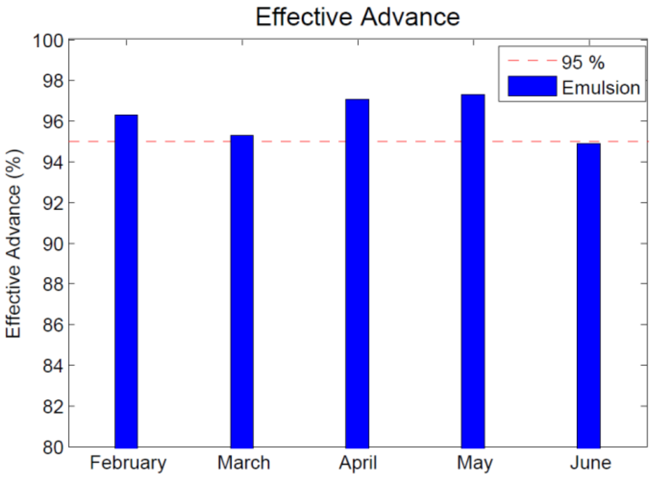


Figure 4.10: Effective advance using emulsion

From this study, we can identify many reasons why emulsions are more effective:

- The brisance of emulsions is higher than ANFO. This is particularly important given that the rock at El Teniente is highly competent.
- The VOD of ANFO is lower than VOD of emulsion. This is particularly important in the case of underground developments where the diameter of drilling is small, and the VOD of ANFO is smaller than theoretical values.
- Emulsions have higher water resistance than ANFO. This is particularly important at El Teniente where water is an issue and is observed at the mining fronts.

Conclusions

In this paper the performance of emulsions and ANFO was studied and compared in the horizontal development process. We focused on the number of boreholes, poisonous gas dilution, effective advance and overbreak. For these topics, emulsions perform better than ANFO in hard competent rock.

In terms of the number of boreholes, a reduction of 13% and 12% in haulage drift and production drift respectively using emulsion was achieved. This represents a savings in the time of drilling activity and, therefore, in the mining cycle time. Poisonous gas dilution time was reduced by 38 minutes on average when the faces were blasted using emulsions; therefore, there is a decrease in the ventilation time.

The average of effective advance by blasting indicates better advance per blasting when emulsions are used; this will influence the total progress of construction through an increase in advance rate and the possibility of faster access to the mineral. Furthermore, the percentage of overbreak was seen to be directly related to linear charge concentration in the perimeter hole. It has been observed that a low linear charge concentration will reduce the overbreak produced by the blast. To improve results, using decoupled charges, maintaining an S/B relation of 0.8 and a shorter delay time in perimeter hole detonation are recommended.

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Chapter 5

Conclusions

The processes included in this study were those involved in the constructive cycle of horizontal developments in which uncertainties and random behaviors are commonly present. As a result of these uncertainties, planning progress goals using analytical methods is often imprecise. The use of tools such as the discrete event simulation has the advantage of incorporating variability into process times by including interferences and real restrictions to operation.

Large-scale underground mines require methods that can help in the elaboration of complex plans, especially when the influence of interference in the excavation cycle is so high. The model developed using SimMine software allowed scenarios considering real interferences in the operation to be compared. Through this comparison it was possible to estimate the impacts of these interferences within the construction cycle and in the short-term progress plans of the horizontal developments for a mine operated by Panel Caving.

The SimMine software was found to have the potential to support decision making in mining development as it is useful to evaluate risks and detect bottlenecks in the progress. Furthermore, this 3D visualization environment allows the behavior of the simulation model to be verified and increases client confidence through the use of animation. This software does have limitations for vertical task construction; however, vertical development was not a constraint in this study. Another issue with SimMine was the significant time invested in the debugging of errors, which had to be addressed during the construction of the model through collaboration with the SimMine programmers.

Drilling and blasting are fundamental activities in the conventional development of tunnels. The choice of explosives to use plays a fundamental role, and thus it is important to evaluate the traditionally used explosive, ANFO, in comparison to alternatives to ensure efficiency and cost effectiveness. In this study, emulsions were found to have better performance in competent rock with respect to ANFO, the explosive traditionally used in Chile. Better performance of emulsions was noted in terms of number of boreholes, dilution of gases, and effective advance. Specifically, the data obtained in field tests showed that use of the emulsion in horizontal developments:

- Increased the advance in meters per round
- Required a smaller number of boreholes to achieve effective advances at more than 95% efficiency in most cases
- Decreased the ventilation time necessary for the evacuation of toxic gases
- Resulted in less overbreak when using non-coupled explosives that have low concentrations of linear charge in the contours

Future Work

Based on this study, further investigation should be done to:

- Perform a more complete time study of the excavation cycle to quantify the impact of each of the interferences between and during unit operations separately.
- Expand the scope of the simulation model, including vertical developments and civil construction, as these tasks together with the horizontal developments are critical in the mining development phase.
- Measure the time needed to conduct each unit operation after blasting when the explosive used is emulsion to quantify the impact of changing the explosive in the excavation cycle.
- Analyze the performance of emulsions further to obtain more information about the fragmentation obtained with this explosive and to measure vibrations in the near field and VOD with borehole diameters of 51 mm, which are currently being used in the mine.
- Analyze operational variables that may influence the performance of explosives. For example, it is necessary to analyze external variables, such as drilling which can have a negative impact in blasting results if drilling precision is lacking.

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APPENDICES

APPENDIX A: Simulation using emulsion

The process of simulation proved to be valuable in the improvement of development planning. The model was utilized to estimate short term horizontal developments and different scenarios were tested. As part of this research, another scenario based on the results obtained in paper II about emulsion explosive was tested.

The simulation model calibrates in paper I, has the following characteristics:

Development cycle: a triangular distribution is used to sample the cycle time per activity the unit operations for excavation cycle. The times of execution of each one of unit operations and the interferences times are specified in the appendix B.

1. Face profile:
   - Haulage drift: 4.2 x 3.9 m
   - Production drift: 4.1 x 3.9 m
2. Shifts: two shifts per day having 6.3 hours per shift
3. Scenario analysis:

   Test and report on scenario with emulsion of explosive type. The results obtained in paper II allows simulate the new scenario varying the following characteristics:

   - Number of boreholes:
     - Haulage drift: -13%
     - Production drift: -12%
   - Advance per round: 96 ± 6%
   - Overbreak: 15 ± 9%
   - Ventilation time: 43 ± 12 minutes

   In terms of development cycle, it means:

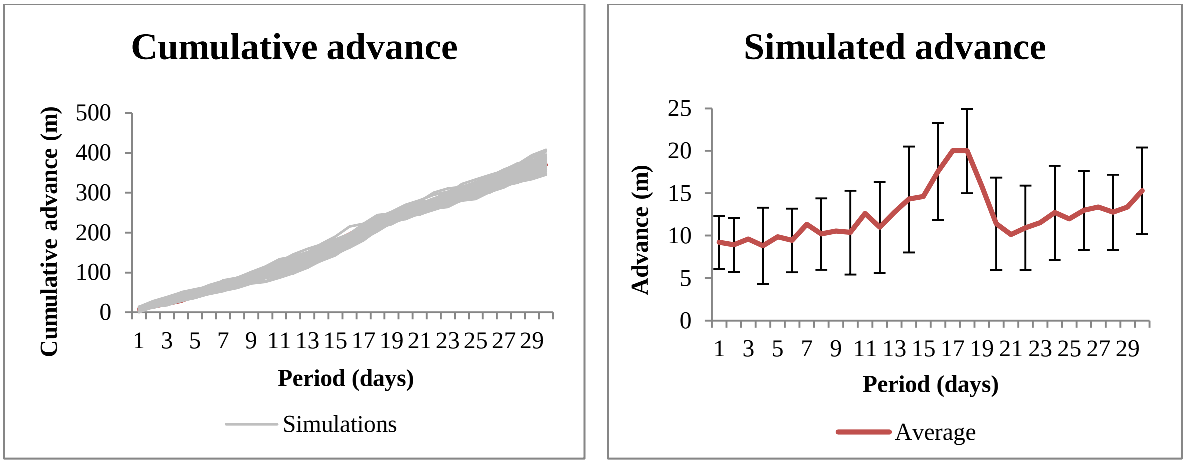
Table A.1: Variables for base case and the new scenario using emulsion

	Base case	Emulsion case
Number of boreholes	54 un	48 un
Drilling depth	3.8 m	3.8 m
Advance per round	3.2 m	Triangular Distribution (a = 3, b = 3.8, c = 3.6)
Effective advance	84 %	96 ± 6%
Overbreak	21%	Normal Distribution ($\mu = 15.8$, $\sigma = 9.2$)
Ventilation time	120 min	43 ± 12 min

4. Results:

Table A.2: Real and simulated advance rate

	Period [days]	Advance [m]	Advance rate [m/day]	Increment [%]
Real	30	316.2	10.5	
Simulated	30	373.9 ± 11.8	12.5± 0.4	17.9 ± 3.4



(a) (b)

Figure A.1: Advance simulated using emulsion (a) cumulated (b) daily

The results of a new scenario using emulsion, indicates a potential increase of 17.9 ± 3.4 % in the advance of horizontal developments even considering interferences. In this case study dynamic simulation has proven to be a valuable means for determining horizontal developments rates and furthermore, allows conducting detailed trade-off work using real data from DET layout.

APPENDIX B: Processes and interferences time

1. Time of Unit Operations

Face	Times of unit operations [minutes]								
	Drilling	Charging	Mucking	Scaling	Bolting	Grouting	Meshing	Hilteo	Shotcreting
Face 1	177	90	136	105	209		105	150	45
						120	93	90	90
Face 2	196	74	210	105	135	120	135	105	
							92	92	119
Face 3	192	105	195	76	150	136	135		
							125	136	105
Face 4	238	106	152	91	135	106	105	135	60
	135								90
Face 5					180	133	138	117	45
		107	180						
Face 6					165	135	135	135	45
	121	105	150	105	150				
Face 7								105	75
	120	89	137	89	169	117			
Face 8					210	120	120	136	104
	165	104	140	90	151	120	135		
Face 9								120	53
	139	90							
Face 10									60
	137	75							
Face 11						135	120	119	55
	152	75							
Face 12									75
	150	75							

Number	12	12	8	7	10	10	12	12	14

Minimum	120	74	136	76	135	106	92	90	45
Average	160	91	163	94	165	124	120	120	73
Mode	#N/A	75	#N/A	105	135	120	135	105	45
Maximum	238	107	210	105	210	136	138	150	119

2. Interferences between unit operations

Face	Drilling	No activity	Charging	No activity	Mucking	No activity	Scaling	No activity	Bolting	No activity	Grouting	No activity	Meshing	No activity	Hilteo	No activity	Shotcreting	No activity
Face 1	177	15	90	60	136	330	105	30	209			465	105	150	150	240	45	225
										75	120	150	93	150	90	30	90	
Face 2	196	165	74	450	210	60	105	0	135	300	120	315	135	75	105	225		30
												180	92	75	92	120	119	
Face 3	192	255	105	180	195	0	76	135	150	60	136	240	135					105
												15	125	95	136	0	105	
Face 4	238	300	106	30	152	15	91	15	135	105	106	225	105	285	135	225	60	75
	135															15	90	375
Face 5								195	180	135	133	615	138	0	117	180	45	
		75	107	180	180													
Face 6								30	165	555	135	225	135	30	135	225	45	
	121	15	105	15	150	375	105	75	150	210								165
Face 7														675	105	270	75	
	120	0	89	180	137	15	89	165	169	60	117	240						105
Face 8								15	135	120	120	135	120	180	136	15	104	
	165	390	104	420	140	45	90	15	151	150	120	75	135	210				60
Face 9															120	15	53	
	139	420	90															60
Face 10																330	60	
	137	240	75															225
Face 11											135	315	120	60	119	15	55	
	152	30	75															120
Face 12																315	75	
	150	45	75															165

Total (min)	1922	1950	1095	1515	1300	840	661	675	1310	1770	1242	3195	1438	1985	1440	2220	1021	1710
Total (hours)	32	33	18	25	22	14	11	11	22	30	21	53	24	33	24	37	17	29

N° Data	12	12	12	8	8	7	7	10	10	10	10	13	12	12	12	15	14	12

Min	120	0	74	15	136	0	76	0	104	60	106	15	92	0	90	0	45	30
Avg	160	163	91	189	163	120	94	68	131	177	124	246	120	165	120	148	73	143
Mod	#N/A	15	75	180	#N/A	15	105	15	135	60	120	315	135	150	105	15	45	225
Max	238	420	107	450	210	375	105	195	184	555	136	615	138	675	150	330	119	375

Probability		92%		100%		86%		90%		100%		100%		92%		93%		100%

3. Interferences during unit operations

Interferences	Drilling		Charging		Mucking	
	Frequency	Time (min)	Frequency	Time (min)	Frequency	Time (min)
Water	5	13	11	11		
Equipment not available	11	86			3	70
Operative failures	42	153	16	21		
Scaling	11	21	11	11	6	36
Disturbed rock						
HSEQ	5	6			6	13
Lack of materials	16	56	16	31		
Lack of workers	11	40				
Ventilation					3	37
Passage persons/equipment					52	103
Ore pass availability					29	123
Total		375		74		382

Interferences	Scaling		Bolting		Grouting	
	Frequency	Time (min)	Frequency	Time (min)	Frequency	Time (min)
Water						
Equipment not available	30	44	14	42		
Operative failures			50	127	33	16
Scaling			14	29		
Disturbed rock	60	109				
HSEQ	10	17				
Lack of materials			7	121	67	82
Lack of workers						
Ventilation			7	10		
Passage persons/equipment			7	15		
Ore pass availability						
Total		170		344		98

Interferences	Meshing		Hilteo		Shotcreting	
	Frequency	Time (min)	Frequency	Time (min)	Frequency	Time (min)
Water	9	15	10	30		
Equipment not available			20	53	60	99
Operative failures					30	60
Scaling	27	41	20	44		
Disturbed rock						
HSEQ	9	9				
Lack of materials	36	70	40	49	10	22
Lack of workers	18	28	10	16		
Ventilation						
Passage persons/equipment						
Ore pass availability						
Total		163		192		181

APPENDIX C: Kolmogorov-Smirnov Goodness of fit test

The Kolmogorov-Smirnov test is used to decide if a sample comes from a population with a specific distribution.

Let x_1, x_2, …, x_n be a random sample of the F distribution. The empirical distribution function F(x) is a function of x, which equals the fraction of x_is that are less than or equal to x for each x, $-\infty < x < \infty$, i.e:

$$F_n(x) = \frac{1}{n}\sum_{i=1}^{n} I(x_i \leq x)$$

Where

$$I(x_i \leq x) = \begin{cases} 1 \; si \; x_i \leq x, \\ 0 \; si \; x_i > x \end{cases}$$

The Kolmogorov-Smirnov test is defined by:

H_0: the data follow a specified distribution
H_a: the data not follow the specified distribution

The Kolmogorov-Smirnov test statistic is defined as:

$$D_n = sup_x|F_n(x) - F_0(x)| = max_{1 \leq i \leq n}\left\{max\left[F_0\left(x_{(i)}\right) - \left(\frac{i-1}{n}\right), \frac{i}{n} - F_0(x_{(i)})\right]\right\}$$

The test statistic is the greatest (denoted by “sup”) vertical distance between F_n and the distribution F_0.

The null hypothesis is rejected if the test statistic, D_n, is greater than the critical value obtained from a table at the level of significance α.

The decision can be carried out also by using the $p - value$ associated with the observed D statistic. The $p - value$ is defined:

$$p - value = P(D > D_{obs}/\, H_0 \; is \; true)$$

For a level of significance α, the decision rule is:

$$p - value \; \geq \; \alpha \; \rightarrow Accept \; H_0$$
$$p - value \; < \; \alpha \; \rightarrow Reject \; H_0$$

Obtaining the $p - value$ requires knowing the distribution of D under the null hypothesis and making the corresponding calculation. In the particular case of the Kolmogorov test, most statistical software packages perform this calculation and provide the $p - value$ directly.

1. **Drilling**

Statistic	Data
N°	12
Mean [min]	160.2
Standard Deviation [min]	35.2
Minimum [min]	120
Maximum [min]	238

H_0: the sample follows a triangular distribution (a = 118, b = 240, c = 130)
H_a: the does not follow a triangular distribution (a = 118, b = 240, c = 130)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.177
p-value	0.787
α	0.05

As the p-value value is greater than the significance level $\alpha = 0.05$, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 118, b = 240, c = 130).

2. **Charging**

Statistic	Data
N°	12
Mean [min]	91.3
Standard Deviation [min]	13.8
Minimum [min]	74
Maximum [min]	107

H_0: the sample follows a triangular distribution (a = 64, b = 118, c = 90)
H_a: the does not follow a triangular distribution (a = 64, b = 118, c = 90)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.287
p-value	0.228
α	0.05

As the p-value value is greater than the significance level $\alpha = 0.05$, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 64, b = 118, c = 90).

3. Scaling

Statistic	Data
N°	7
Mean [min]	94.4
Standard Deviation [min]	11.1
Minimum [min]	76
Maximum [min]	105

H_0: the sample follows a triangular distribution (a = 70, b = 110, c = 105)
H_a: the does not follow a triangular distribution (a = 70, b = 110, c = 105)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.304
p-value	0.452
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 70, b = 110, c = 105).

4. Bolting

Statistic	Data
N°	10
Mean [min]	165.4
Standard Deviation [min]	738.5
Minimum [min]	135
Maximum [min]	210

H_0: the sample follows a triangular distribution (a = 100, b = 230, c = 135)
H_a: the does not follow a triangular distribution (a = 100, b = 230, c = 135)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.157
p-value	0.935
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 100, b = 230, c = 135).

5. Grouting

Statistic	Data
N°	10
Mean [min]	124.2
Standard Deviation [min]	10.0
Minimum [min]	106
Maximum [min]	136

H_0: the sample follows a triangular distribution (a = 100, b = 140, c = 120)
H_a: the does not follow a triangular distribution (a = 100, b = 140, c = 120)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.339
p-value	0.159
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 100, b = 140, c = 120).

6. Meshing

Statistic	Data
N°	12
Mean [min]	119.8
Standard Deviation [min]	17.1
Minimum [min]	92
Maximum [min]	138

H_0: the sample follows a triangular distribution (a = 90, b = 140, c = 135)
H_a: the does not follow a triangular distribution (a = 90, b = 140, c = 135)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.317
p-value	0.144
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 90, b = 140, c = 135).

7. Hilteo

Statistic	Data
N°	12
Mean [min]	120
Standard Deviation [min]	19.1
Minimum [min]	90
Maximum [min]	150

H_0: the sample follows a triangular distribution (a = 85, b = 155, c = 135)
H_a: the does not follow a triangular distribution (a = 85, b = 155, c = 135)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.233
p-value	0.462
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 85, b = 155, c = 135).

8. Shotcreting

Statistic	Data
N°	14
Mean [min]	72.9
Standard Deviation [min]	24.9
Minimum [min]	45
Maximum [min]	119

H_0: the sample follows a triangular distribution (a = 44, b = 132, c = 45)
H_a: the does not follow a triangular distribution (a = 44, b = 132, c = 45)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.203
p-value	0.545
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 44, b = 132, c = 45).

9. Interference between shotcreting and drilling

Statistic	Data
N°	12
Mean [min]	142.5
Standard Deviation [min]	96.7
Minimum [min]	30
Maximum [min]	375

H_0: the sample follows a triangular distribution (a = 20, b = 400, c = 100)
H_a: the does not follow a triangular distribution (a = 20, b = 400, c = 100)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.271
p-value	0.286
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 20, b = 400, c = 100).

10. Interference between drilling and charging

Statistic	Data
N°	11
Mean [min]	177.3
Standard Deviation [min]	152.2
Minimum [min]	15
Maximum [min]	420

H_0: the sample follows a triangular distribution (a = 5, b = 450, c = 100)
H_a: the does not follow a triangular distribution (a = 5, b = 450, c = 100)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.339
p-value	0.125
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 5, b = 450, c = 100).

11. Interference between blasting and mucking

Statistic	Data
N°	8
Mean [min]	189.4
Standard Deviation [min]	166.4
Minimum [min]	15
Maximum [min]	450

H_0: the sample follows a triangular distribution (a = 10, b = 500, c = 180)
H_a: the does not follow a triangular distribution (a = 10, b = 500, c = 180)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.403
p-value	0.110
α	0.05

As the p-value value is greater than the significance level $\alpha = 0.05$, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 10, b = 500, c = 180).

12. Interference between mucking and scaling

Statistic	Data
N°	6
Mean [min]	140
Standard Deviation [min]	166.1
Minimum [min]	15
Maximum [min]	375

H_0: the sample follows a triangular distribution (a = 3, b = 450, c = 50)
H_a: the does not follow a triangular distribution (a = 3, b = 450, c = 50)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.517
p-value	0.051
α	0.05

As the p-value value is greater than the significance level $\alpha = 0.05$, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 3, b = 450, c = 50).

13. Interference between scaling and bolting

Statistic	Data
N°	9
Mean [min]	75.0
Standard Deviation [min]	71.5
Minimum [min]	15
Maximum [min]	195

H_0: the sample follows a triangular distribution (a = 1, b = 230, c = 30)
H_a: the does not follow a triangular distribution (a = 1, b = 230, c = 30)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.429
p-value	0.051
α	0.05

As the p-value value is greater than the significance level $\alpha = 0.05$, the null hypothesis H_0 is accepted. It cannot reject that the data follows a triangular distribution (a = 1, b = 230, c = 30).

14. Interference between bolting and grouting

Statistic	Data
N°	10
Mean	177
Variance	23090
Minimum	60
Maximum	555

H_0: the sample follows a triangular distribution (a = 4, b = 600, c = 120)
H_a: the does not follow a triangular distribution (a = 4, b = 600, c = 120)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.408
p-value	0.051
α	0.05

As the p-value value is greater than the significance level $\alpha = 0.05$, the null hypothesis H_0 is accepted. It cannot be rejected that the data follows a triangular distribution (a = 4, b = 600, c = 120).

15. Interference between grouting and meshing

Statistic	Data
N°	13
Mean [min]	245.8
Standard Deviation [min]	158.9
Minimum [min]	15
Maximum [min]	615

H_0: the sample follows a triangular distribution (a = 10, b = 700, c = 240)
H_a: the does not follow a triangular distribution (a = 10, b = 700, c = 240)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.359
p-value	0.053
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot be rejected that the data follows a triangular distribution (a = 10, b = 700, c = 240).

16. Interference between meshing and hilteo

Statistic	Data
N°	11
Mean [min]	180.5
Standard Deviation [min]	180.3
Minimum [min]	30
Maximum [min]	675

H_0: the sample follows a triangular distribution (a = 10, b = 700, c = 90)
H_a: the does not follow a triangular distribution (a = 10, b = 700, c = 90)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.389
p-value	0.053
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot be rejected that the data follows a triangular distribution (a = 10, b = 700, c = 90).

17. Interference between hilteo and shotcreting

Statistic	Data
N°	14
Mean [min]	158.6
Standard Deviation [min]	120.0
Minimum [min]	15
Maximum [min]	330

H_0: the sample follows a triangular distribution (a = 3, b = 360, c = 225)
H_a: the does not follow a triangular distribution (a = 3, b = 360, c = 225)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.348
p-value	0.051
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot be rejected that the data follows a triangular distribution (a = 3, b = 360, c = 225).

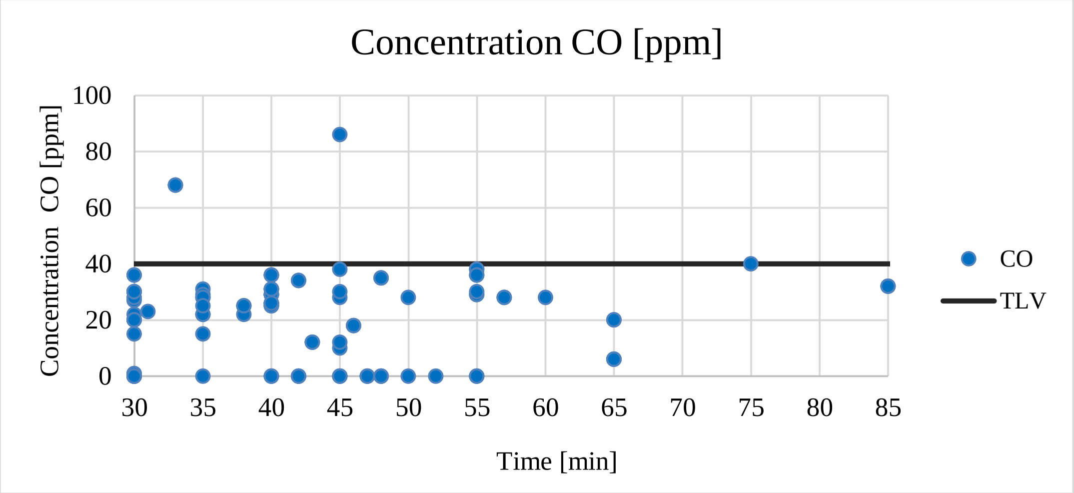
APPENDIX D: Data of emulsion and ANFO study

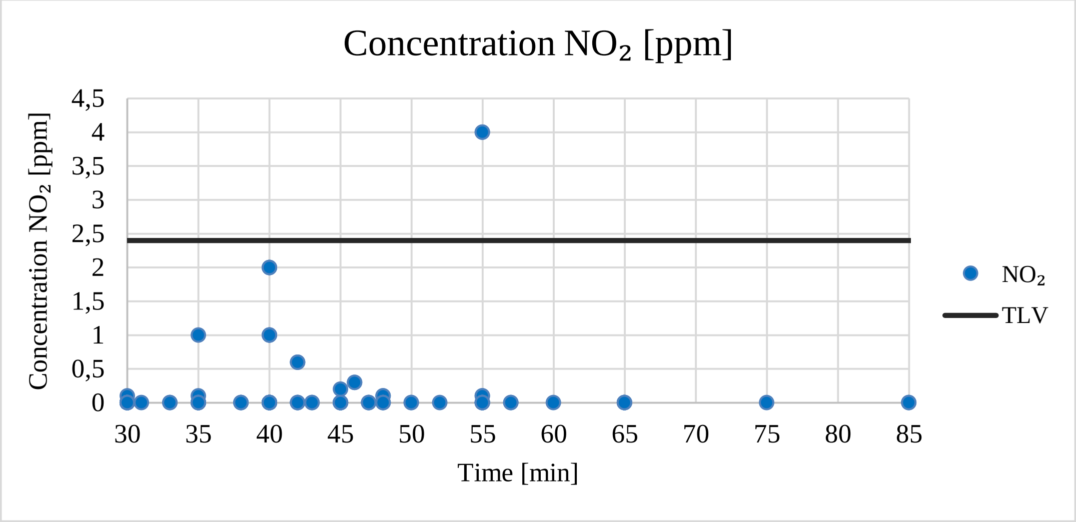
1. Ventilation (emulsion)

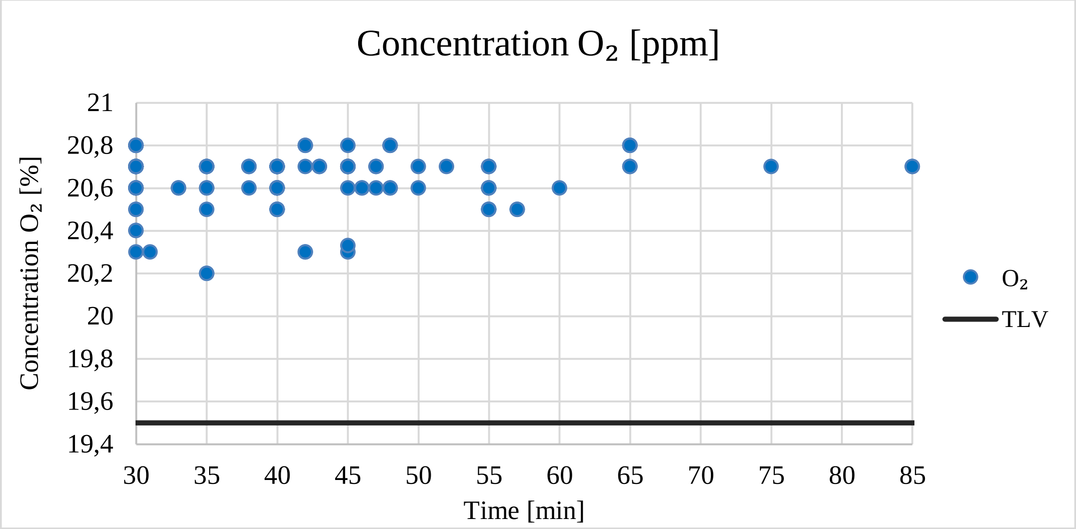
Ventilation time (hh:mm)	CO (ppm)	NO$_2$ (ppm)	O$_2$ (%)	Ventilation time (hh:mm)	CO (ppm)	NO$_2$ (ppm)	O$_2$ (ppm)
0:30	15	0	20,6	0:38	25	0	20,7
0:30	0	0	20,6	0:38	25	0	20,7
0:30	27	0,1	20,7	0:40	29	0	20,7
0:30	28	0	20,4	0:40	29	0	20,7
0:30	22	0	20,3	0:40	26	2	20,7
0:30	0	0	20,7	0:40	31	1	20,5
0:30	20	0	20,8	0:40	0	0	20,5
0:30	20	0	20,8	0:40	0	0	20,7
0:30	20	0	20,8	0:40	36	0	20,6
0:30	0,9	0	20,7	0:40	26	2	20,7
0:30	0,9	0	20,7	0:40	26	2	20,7
0:30	30	0	20,7	0:40	29	0	20,6
0:30	30	0	20,4	0:40	29	0	20,6
0:30	30	0	20,5	0:40	31	1	20,5
0:30	30	0	20,5	0:40	31	1	20,5
0:30	36	0	20,6	0:40	0	0	20,7
0:30	36	0	20,6	0:40	25	0	20,6
0:30	0	0	20,7	0:40	25	0	20,6
0:30	0	0	20,6	0:40	25	0	20,7
0:30	0	0	20,8	0:40	26	0	20,7
0:30	0	0	20,7	0:40	36	0	20,6
0:30	0	0	20,7	0:40	36	0	20,6
0:30	20	0	20,6	0:42	34	0,6	20,3
0:30	0	0	20,8	0:42	34	0,6	20,3
0:30	0	0	20,7	0:42	0	0	20,7
0:31	23	0	20,3	0:42	0	0	20,8
0:33	68	0	20,6	0:42	0	0	20,8
0:33	68	0	20,6	0:43	12	0	20,7
0:35	22	0	20,2	0:43	12	0	20,7
0:35	15	0,1	20,6	0:45	10	0	20,7
0:35	22	0	20,2	0:45	28	0	20,7
0:35	31	1	20,6	0:45	30	0	20,6
0:35	29	0	20,5	0:45	0	0	20,7
0:35	28	0	20,7	0:45	12	0	20,3
0:35	28	0	20,7	0:45	38	0	20,7
0:35	25	0	20,7	0:45	0	0	20,7
0:35	0	0	20,7	0:45	0	0	20,7
0:38	22	0	20,6	0:45	86	0,2	20,33

Ventilation time (hh:mm)	**CO (ppm)**	**NO_2 (ppm)**	**O_2 (ppm)**	**Ventilation time (hh:mm)**	**CO (ppm)**	**NO_2 (ppm)**	**O_2 (ppm)**
0:45	0	0	20,8	0:55	29	0	20,5
0:46	18	0,3	20,6	0:55	29	0	20,5
0:46	18	0,3	20,6	0:55	30	0	20,7
0:47	0	0	20,7	0:55	0	0	20,5
0:47	0	0	20,7	0:55	0	0	20,7
0:47	0	0	20,6	0:55	0	0	20,7
0:48	35	0,1	20,6	0:57	28	0	20,5
0:48	35	0,1	20,6	0:57	28	0	20,5
0:48	0	0	20,8	1:00	28	0	20,6
0:48	0	0	20,8	1:05	20	0	20,7
0:48	0	0	20,8	1:05	20	0	20,7
0:50	28	0	20,6	1:05	6	0	20,8
0:50	0	0	20,7	1:05	6	0	20,8
0:52	0	0	20,7	1:05	6	0	20,8
0:55	38	0,1	20,6	1:15	40	0	20,7
0:55	38	0,1	20,6	1:25	32	0	20,7
0:55	36	4	20,6	1:25	32	0	20,7
0:55	36	4	20,6				

Statistic	Data
N°	111
Mean [min]	43
Standard deviation [min]	12
Minimum [min]	30
Maximum [min]	85







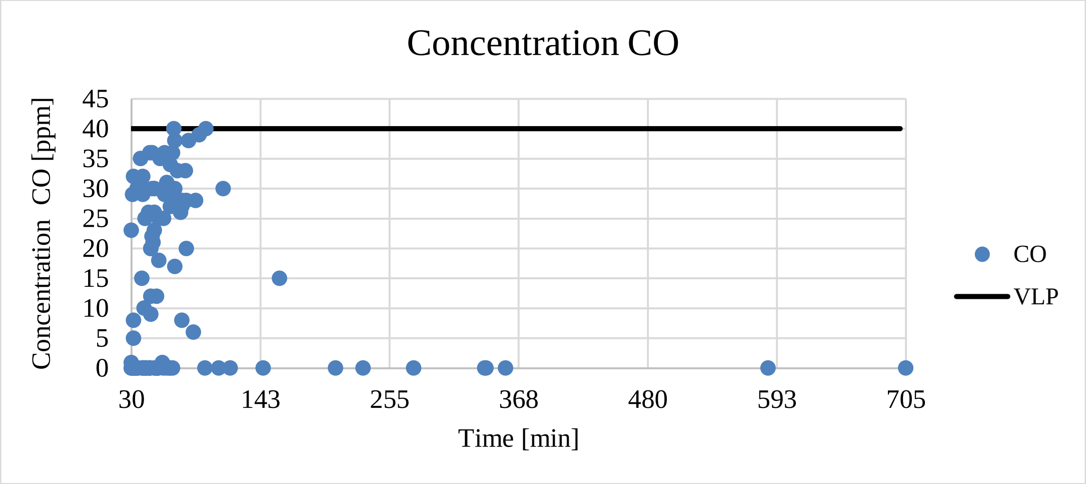
2. Ventilation (ANFO)

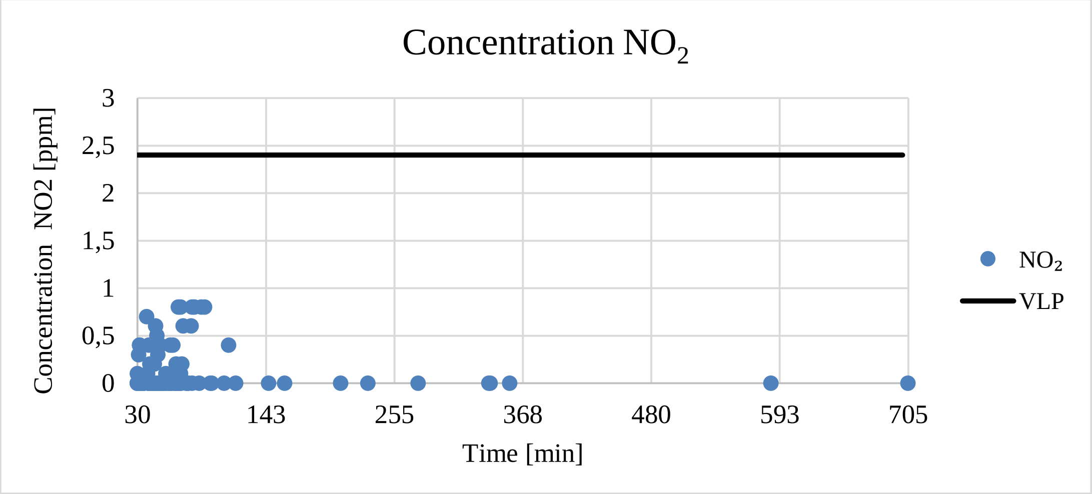
Ventilation time [hh:mm]	**CO [ppm]**	**NO$_2$ [ppm]**	**O$_2$ [%]**	**Ventilation time [hh:mm]**	**CO [ppm]**	**NO$_2$ [ppm]**	**O$_2$ [ppm]**
0:41	10	0,2	20,8	5:38	0	0	20,8
0:35	0	0	20,8	3:28	0	0	20,8
0:46	36	0,6	20,7	1:18	28	0,8	20,8
0:54	18	0	20,7	5:56	0	0	20,8
0:57	0,9	0	20,7	1:26	28	0,8	20,6
0:32	32	0,4	20,8	2:39	15	0	20,8
1:04	29	0,2	20,8	1:34	0	0	20,8
0:50	30	0,4	20,7	0:34	0	0	20,8

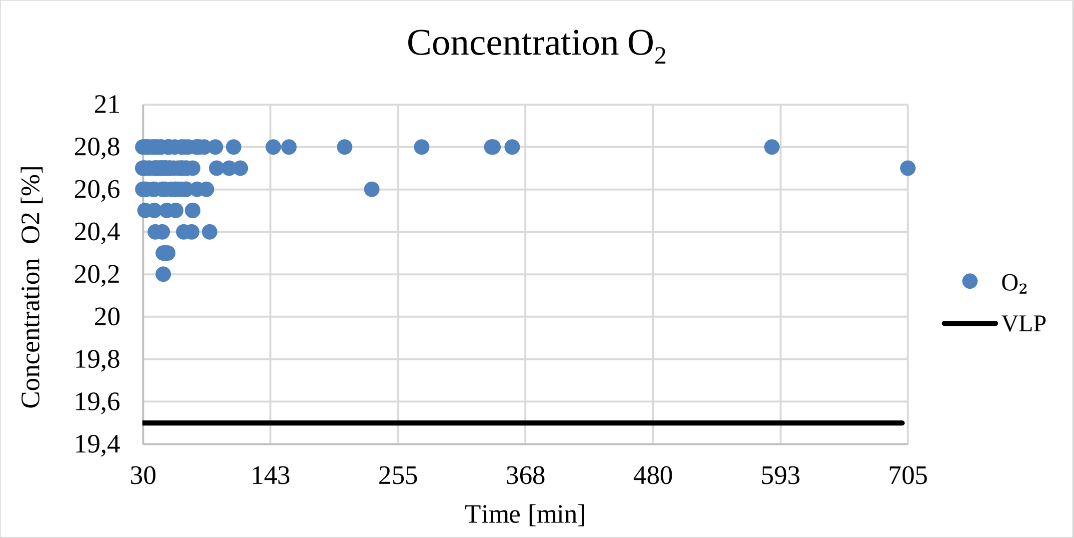
Ventilation time [hh:mm]	**CO [ppm]**	**NO_2 [ppm]**	**O_2 [%]**	**Ventilation time [hh:mm]**	**CO [ppm]**	**NO_2 [ppm]**	**O_2 [ppm]**
1:50	30	0,4	20,8	0:45	26	0,2	20,7
1:20	38	0,8	20,8	0:59	36	0,4	20,6
0:46	0	0	20,8	0:49	21	0	20,7
0:38	35	0,7	20,8	0:59	29	0	20,5
0:40	0	0	20,8	0:35	30	0	20,7
0:47	20	0,5	20,7	0:41	30	0	20,4
1:10	33	0,6	20,8	1:14	27	0	20,5
1:17	33	0,6	20,8	0:30	0	0	20,8
1:01	31	0,4	20,6	9:45	0	0	20,8
1:08	38	0,8	20,6	2:25	0	0	20,8
11:45	0	0	20,7	5:39	0	0	20,8
1:06	36	0,8	20,4	3:52	0	0	20,6
1:29	39	0,8	20,4	4:36	0	0	20,8
1:18	20	0	20,6	0:32	8	0,4	20,5
1:04	34	0	20,6	0:40	0	0	20,6
1:09	28	0,2	20,7	1:14	28	0	20,5
0:40	32	0,4	20,7	0:51	0	0	20,7
0:31	29	0,3	20,6	0:33	0	0	20,6
0:55	35	0,1	20,6	0:54	25	0	20,7
0:42	25	0	20,7	1:08	30	0	20,7
0:53	0	0	20,8	1:04	27	0	20,7
0:30	23	0,1	20,6	1:08	17	0,1	20,6
0:48	30	0,3	20,7	0:42	0	0	20,7
0:32	0	0	20,7	1:46	0	0	20,7
0:42	0	0	20,7	1:56	0	0	20,7
1:04	0	0	20,7	0:52	12	0	20,3
0:47	12	0	20,4	0:47	9	0	20,7
0:32	5	0	20,7	1:03	0	0	20,7
0:48	22	0	20,3	0:51	0	0	20,5
0:50	23	0	20,3	0:50	30	0	20,6
0:48	22	0	20,2	1:14	8	0	20,7
1:13	26	0	20,4	1:08	28	0	20,6
0:39	15	0,1	20,6	0:58	25	0	20,6
0:31	0	0	20,6	1:01	0	0	20,7
0:40	29	0	20,5	0:50	26	0	20,7
0:30	0,9	0	20,7	0:53	0	0	20,8
0:50	0	0	20,7	0:47	20	0	20,6
0:30	0	0	20,7	1:06	0	0	20,7
0:36	0	0	20,7	1:24	6	0	20,8
0:48	36	0	20,6	0:43	0	0	20,8

Ventilation time [hh:mm]	**CO [ppm]**	**NO_2 [ppm]**	**O_2 [%]**	**Ventilation time [hh:mm]**	**CO [ppm]**	**NO_2 [ppm]**	**O_2 [ppm]**
1:35	40	0	20,7	0:53	0	0	20,7
1:07	40	0	20,8	0:46	0	0	20,7
0:46	0	0	20,8	0:52	0	0	20,8
0:33	0	0	20,8	0:44	0	0	20,7
0:33	0	0	20,8	0:58	0	0	20,8
0:40	0	0	20,7				

Statistic	**Data**
N°	107
Mean [min]	81
Standard Deviation [min]	99
Minimum [min]	30
Maximum [min]	705







3. Overbreak (emulsion)

Date	Overbreak	Date	Overbreak	Date	Overbreak
07-feb	22%	16-mar	19%	20-abr	45%
08-feb	35%	17-mar	13%	21-abr	33%
14-feb	35%	19-mar	28%	23-abr	97%
18-feb	19%	19-mar	38%	26-abr	43%
19-feb	37%	20-mar	27%	03-may	15%
19-feb	39%	23-mar	37%	05-may	45%
20-feb	27%	26-mar	40%	06-may	12%
28-feb	25%	28-mar	37%	07-may	22%
28-feb	14%	28-mar	29%	08-may	10%
01-mar	29%	30-mar	6%	10-may	22%
01-mar	11%	01-abr	44%	10-may	30%
01-mar	32%	03-abr	11%	12-may	22%
04-mar	35%	04-abr	70%	15-may	41%
04-mar	35%	04-abr	44%	16-may	21%
05-mar	9%	05-abr	59%	16-may	0%
06-mar	7%	05-abr	54%	19-may	2%
08-mar	43%	07-abr	64%	20-may	16%
08-mar	5%	08-abr	40%	23-may	27%
08-mar	24%	10-abr	27%	26-may	14%
10-mar	31%	11-abr	27%	31-may	8%
11-mar	26%	12-abr	50%	01-jun	30%
11-mar	21%	13-abr	46%	05-jun	14%
13-mar	30%	15-abr	61%	08-jun	28%

14-mar	48%	16-abr	39%	08-jun	14%
15-mar	47%	16-abr	53%	15-jun	5%
16-mar	31%				

First period from February 7 to May 17 (explosive used in the perimeter holes: emulsion with density of 0.9 g/cm^3.

Statistic	Data
N°	66
Mean [%]	32.4
Standard Deviation [%]	17.1
Minimum [%]	0
Maximum [%]	97

Second period from May 18 to June 30 (explosive used in the perimeter holes: packaged dynamite).

Statistic	Data
N°	10
Mean [%]	15.8
Standard Deviation [%]	9.7
Minimum [%]	2
Maximum [%]	30

The Kolmogorov-Smirnov test was used to decide if the results of overbreak of the second period come from a specific distribution and be able to use in the simulation model.

H_0: the sample follows a normal distribution ($\mu = 15.8$, $\sigma = 9.2$)
H_a: the does not follow a normal distribution ($\mu = 15.8$, $\sigma = 9.2$)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.193
p-value	0.786
α	0.05

As the p-value value is greater than the significance level $\alpha = 0.05$, the null hypothesis H_0 is accepted. It cannot be rejected that the data follows a normal distribution ($\mu = 15.8$, $\sigma = 9.2$).

4. Overbreak (ANFO)

Date	Overbreak
01-feb	14%
01-feb	6%
02-feb	49%
04-feb	21%
04-feb	8%
11-feb	29%
20-feb	40%
26-feb	30%
26-feb	28%
04-mar	25%
08-mar	9%
08-mar	4%
11-mar	14%
13-mar	37%
26-mar	40%
23-abr	0%
28-abr	17%
29-abr	48%
05-may	17%
05-may	46%
08-may	15%
18-may	14%
19-may	26%
22-may	6%
25-may	13%
02-jun	17%

Statistic	Data
N°	22
Mean [%]	22
Standard Deviation [%]	14
Minimum [%]	0
Maximum [%]	49

5. Advance per round (emulsion)

Date	Hole depth [m]	Advance per round [m]	Effective advance	Date	Hole depth [m]	Advance per round [m]	Effective advance
07-feb	3,6	3,6	100%	31-mar	3,7	3,7	100%
10-feb	3,0	2,6	85%	31-mar	3,3	2,5	75%
14-feb	3,6	3,4	96%	01-abr	3,8	3,8	100%
18-feb	3,1	3,1	100%	03-abr	3,7	3,4	94%
18-feb	3,5	3,5	100%	04-abr	3,8	3,5	93%
19-feb	3,3	3,3	100%	05-abr	3,7	3,7	100%
19-feb	3,5	3,2	93%	05-abr	3,8	3,4	89%
20-feb	3,4	3,4	100%	06-abr	3,7	3,7	100%
21-feb	3,4	3,4	100%	07-abr	3,8	3,7	98%
21-feb	3,7	3,7	100%	08-abr	3,4	3,3	97%
24-feb	3,7	3,7	100%	10-abr	3,5	3,5	100%
28-feb	3,2	3,1	98%	12-abr	3,5	3,5	100%
28-feb	3,7	2,9	79%	12-abr	3,7	3,7	100%
01-mar	3,4	3,4	100%	13-abr	3,5	3,5	100%
01-mar	3,4	3,4	100%	15-abr	3,8	2,8	75%
01-mar	3,7	3,7	100%	16-abr	3,7	3,7	100%
04-mar	3,5	3,5	100%	16-abr	3,6	3,6	100%
04-mar	3,4	3,4	100%	17-abr	3,7	3,6	96%
05-mar	3,3	3,2	96%	20-abr	3,7	3,6	98%
07-mar	3,8	3,4	88%	20-abr	3,5	3,4	99%
08-mar	3,7	3,0	83%	21-abr	2,8	2,8	100%
08-mar	3,6	3,1	86%	21-abr	3,0	2,9	96%
10-mar	3,6	3,1	87%	23-abr	3,0	3,0	100%
11-mar	3,6	3,3	92%	26-abr	3,6	3,6	100%
13-mar	3,7	3,7	100%	02-may	3,4	3,4	100%
14-mar	3,7	3,7	100%	02-may	3,8	3,8	99%
16-mar	3,6	3,6	100%	03-may	2,8	2,8	100%
16-mar	3,8	3,7	98%	05-may	3,4	3,4	100%
17-mar	3,5	3,5	100%	05-may	3,0	2,9	98%
19-mar	3,3	3,3	100%	07-may	3,5	3,5	100%
20-mar	3,1	3,1	100%	08-may	3,7	2,8	75%
20-mar	3,2	3,1	95%	10-may	1,9	1,9	100%
22-mar	3,5	3,1	87%	10-may	3,6	3,3	93%
23-mar	3,3	2,9	88%	11-may	3,7	3,4	93%
26-mar	3,3	3,3	100%	12-may	3,6	3,6	100%
28-mar	3,4	3,4	100%	16-may	3,5	3,5	100%
28-mar	3,5	3,5	100%	18-may	3,7	3,7	100%
30-mar	2,8	2,8	100%	18-may	3,6	3,6	100%
30-mar	3,5	3,3	94%	19-may	2,9	2,9	100%

Date	Hole depth [m]	Advance [m]	Effective advance	Date	Hole depth [m]	Advance [m]	Effective advance
20-may	3,5	3,5	100%	04-jun	3,6	3,6	100%
22-may	3,5	3,2	92%	04-jun	3,2	3,2	100%
23-may	3,6	3,5	97%	05-jun	3,4	3,4	100%
25-may	3,6	3,6	100%	07-jun	3,4	3,1	91%
25-may	3,4	3,4	100%	08-jun	2,7	2,7	100%
26-may	3,0	2,7	91%	09-jun	3,0	3,0	100%
27-may	3,5	3,5	100%	11-jun	3,0	3,0	100%
29-may	3,3	3,3	100%	15-jun	3,6	3,1	86%
30-may	3,7	3,6	98%	22-jun	3,7	3,1	85%
31-may	3,4	3,4	100%	24-jun	3,7	3,7	100%
31-may	3,7	3,6	97%	24-jun	3,7	3,1	85%
01-jun	3,6	3,3	91%				

Statistic	Advance per round	Effective advance
N°	101	101
Mean	3.3 [m]	96 [%]
Standard deviation	0.3 [m]	6 [%]
Minimum	1.9 [m]	75 [%]
Maximum	3.8 [m]	100 [%]

The Kolmogorov-Smirnov test was used to decide if the results of advance per round come from a specific distribution and to be incorporated in the simulation model.

H_0: the sample follows a triangular distribution (a = 3, b = 3.8, c = 3.6)
H_a: the does not follow a triangular distribution (a = 3, b = 3.8, c = 3.6)

When performing the Kolmogorov-Smirnov test with XLSTAT, the following results are obtained:

D	0.135
p-value	0.069
α	0.05

As the p-value value is greater than the significance level α = 0.05, the null hypothesis H_0 is accepted. It cannot be rejected that the data follows a normal distribution (a = 3, b = 3.8, c = 3.6).

APPENDIX E: Work mode SimMine

The work mode defines how equipment will select work, and how they enter work times. The overall functionality is that when a vehicle searches for work, it will select one of the three modes: highest priority, most meters/week and closest distance. The work modes are as follow:

- Highest priority: the locations that have the highest set priority will be selected first for working at. The smaller priority number, the higher priority (i.e. Priority 1 is highest).The number of priority of the faces is delivered by user and the face must be selected manually. When two or more faces are available for a unit operation to be developed, the equipment will go to the face with the highest priority.

- Most meters/week: this priority is calculated that a face that needs more meters per week until finished compared to a second section, that section will be higher in priority. This mode requires that a desired end date is specified on the end sections (i.e the sections at the end of the development). Equipment will select work where the most number of meters per week needs to be performed until it must be completed. In this priority mode, the priority will change during the development.

- Closest distance: the equipment allocations are prioritized depending on the driving distance for the vehicle. The work faces that require the equipment to travel as little as possible is selected first.