



PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE
ESCUELA DE INGENIERÍA

**MATHEMATICAL MODELLING OF BLASTING
DECISIONS USING AN INTEGRATED OPEN PIT
MINE TO MILL MODEL**

ANDRÉS EMILIO PÉREZ ERRÁZURIZ

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:

ALEJANDRO FRANCISCO MAC CAWLEY VERGARA

Santiago de Chile, November 2017

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ABSTRACT

In price sensitive industries, such as the mining industry, cost and productivity are key drivers. So making the right decisions to reduce expenses and increase the throughput of the process can make the difference when trying to stay active in fast-changing market.

The concept of Mine to Mill corresponds to all models which integrate the complete mining processes, from blasting decisions up to the mill decisions. These decision making models look to enhance the performance of all downstream processing activities. In this thesis we will study the variables that are involved in blasting stage of an open pit mine operation and how they affect the economic performance of the mine. The research questions are: Is it possible to create an integrated mathematical model of all the mining processes? Can we determine a relationship between the blasting variables and overall energy consumption? Is there a blasting design that maximizes the operation productivity reducing the resources consumption?

The contribution of this work is to analyze the impact of blasting decisions in the cost structure and energy consumption of an open pit mine operation, by developing a mathematical model that evaluates the operational and economic performance under any equipment configuration. It utilizes existing mathematical models of the drilling, blasting, crushing and grinding processes balancing inputs simplicity and outputs accuracy. A simulation of a Chilean operation shows the blasting design that reduces the cost and energy consumption, increasing the throughput and annual revenues. Results indicate a major increase in the plant throughput and the operation annual revenues, when varying blasting key parameters. For the studied case, increments of 25% in the plant throughput and the annual revenues were observed with a reduction of 15% in the blast diameter and also with an increase of the same magnitude in the powder factor.

Keywords: Mine to Mill, Blasting, Mining, SAG mill, Grinding, Fragmentation, Modeling, Resources.

RESUMEN

En industrias sensibles al precio, como la industria minera, el costo y la productividad son los factores clave. Por lo tanto, tomar las decisiones correctas para reducir los gastos y aumentar el rendimiento del proceso puede marcar la diferencia cuando se trata de mantenerse activo en un mercado que cambia rápidamente.

El concepto de Mine to Mill corresponde a modelos que describen los procesos mineros, desde las decisiones de tronadura hasta las decisiones de la planta. Estos modelos de toma de decisiones buscan mejorar el rendimiento de todos los procesos aguas abajo. En esta tesis estudiaremos las variables que están involucradas en la etapa de tronadura de una mina a cielo abierto y cómo afectan el desempeño económico de la mina. Las preguntas de investigación son: ¿Es posible crear un modelo matemático integrado de todos los procesos mineros? ¿Podemos determinar una relación entre las variables de tronadura y el consumo total de energía? ¿Hay un diseño de tronadura que maximiza la productividad de la operación reduciendo el consumo de recursos?

La contribución de este trabajo es analizar el impacto de las decisiones de tronadura en los costos y el consumo de energía de una operación minera a cielo abierto, mediante el desarrollo de un modelo matemático que evalúa el rendimiento operativo y económico bajo cualquier configuración de los equipos de la mina y planta. Este utiliza modelos matemáticos existentes de los procesos de perforación, tronadura, chancado y molienda balanceando la simplicidad de los inputs y la precisión de los outputs. La simulación de la operación de una mina chilena muestra el diseño de tronadura que reduce el consumo de energía, incrementando el rendimiento y los ingresos anuales. Para el caso estudiado, se observaron incrementos de 25% en el rendimiento de la planta y los ingresos anuales, al reducir en 15% el diámetro de perforación e incrementar el factor de carga en un 15%.

Palabras Clave: Mine to Mill, Tronadura, Minería, Molino SAG, Molienda, Fragmentación, Modelación, Recursos.

1. INTRODUCTION

1.1. Background

1.1.1. Mining Industry Background

The mining industry has always been a very important sector in the Chilean economy. Between 1880 and 1930, Chile was one of the largest saltpeter (potassium nitrate) producer in the world. By 1925 German scientists developed a low-cost synthetic saltpeter, making Chilean natural reserves worthless because they weren't able to compete with the cost spectrum of the European countries. Even though the collapse of the saltpeter industry in Chile, the mining industry has continued to be one of the main economic activities of Chile. In 2016 it accounted for 8% of the Chilean Gross Domestic Product (GDP) and US\$ 30,379 millions in exports, what represents 50.8% of the total national exports. Thus, the mining industry exports have represented more than 50% of the national exports for over the last ten years (Consejo Minero, 2017).

Copper represents 91% of the mining exports of the country and 28% of the global copper production. Chile has 29% of the copper reserves of the world. Since 2011, copper price has experienced a downfall from around US\$ 4 per pound to US\$ 2.21 per pound (Consejo Minero, 2017). This situation has forced the industry actors to incur in efforts to optimize operations, increase productivity and reduce costs to stay competitive in a fast-changing market.

The two main steps during the mining process are: first, the prospection of mineral and second, the extraction. The prospection and detection process is aimed to find an ore resource: a mineral concentration that has enough economic value and its extraction is technically feasible. Then, pursuing further analysis the ore reserves are defined. Ore reserves correspond to the mineral portion that can be economically, technically, operationally and legally extracted. In parallel, an iterative process is carried out to determine the most

suitable extraction method. There are two main kinds: open pit and underground. Open pit mines consider the extraction of material and waste in superficial cones, and underground mines use tunnels to extract only the material with economic value. The research is focused on open pit mines which are widely used in the world due to its low costs and simple engineering process when extracting superficial ore reserves.

Both extracting methods, open-pit and underground, utilize explosives to blast the in-situ ore and fragment the mineral which is later transported by truck or conveyor belts to a comminution plant. Depending on the type of ore, the material will be treated in processing plant where the element of interest is separated from the worthless compounds present in the ore (waste). The treated ore can be sold as a concentrate or be further processes in order to increase its purity.

The mining industry is capital, cost and resources intensive. The comminution stage represents more than a 44% of the total energy consumption of a mining operation and a 21% of the total costs of mining supplies (DOE, 2007). The objective of a mining operation is to extract material bringing forward in time as much cash flow as possible, allowing an increase of the project Net Present value (NPV). Thus, mining operations must increase their processing rate and reduce their production costs to maximize their objective function.

Mine to Mill is a modelling and operating strategy for mining operations to enhance the performance of mining and downstream processing activities (McKee, 2013). This can be translated in the operational integration of the decision making process of all mining stages. Through the optimization of the blasting stage it is possible to observe reduction the particles size fed to the comminution equipment, which leads to an increase in the production efficiency and a reduction of cost and resources consumption.

This work will focus on the development and validation of a mathematical Mine to Mill model which will take into account the extraction and comminution processes, to analyze the key factors in the blasting design that allow a reduction in the costs and resources

consumption, and an increase in the productivity. In order to carry out the research, several mathematical models will be integrated and used to simulate different configurations.

1.1.2. Mining Processes

The material extraction is done through a process referred as drilling and blasting. After determining the ore reserves, the mine is divided in fixed size blocks where each of them has the average grade of the element of interest. A blasting design is defined based on a geological and economical information of the ore reserves. Drilling refers to the process in which several holes are made in the earth surface, following a defined blasting grid. Then, explosives are loaded in those holes to be later blasted breaking the in-situ material. The fragmented ore is loaded into trucks or conveyor belts by front loaders and/or mechanic shovels. Depending on the economical value of the blasted blocks, the loaded material is transported to the waste dump or the comminution plant to be further processed.

In the comminution plant the extracted material undergoes through several size-reduction stages until it reaches a specific size that allows its separation from the worthless elements. The comminution process is separated in two main stages: crushing and grinding, where the first one is in charge of the first size reduction of the in-situ material and the second one of reducing the particles size in general below $200\mu\text{m}$. The material will recirculate several times between different equipment until it reaches the defined size. The crushing and grinding processes accounts for a 4% and 40% of the energy consumption value mentioned in the previous section (DOE, 2007).

When extracting oxide elements, after their size reduction they material is concentrated and consolidated until it reaches a defined size. Then, it is leached with acid to liberate the minerals into the acid solution. Through an electrowinning procedure, the element of interest is extracted in a solid form with enough purity to be sold in the open market.

For sulfide elements, after its liberation in the comminution plant, the ore is sent to the floating plant where the metal of interest is separated from the other elements present in

it. This process is carried out in tanks that create air bubbles that target and adhere only to specific elements. The waste goes to the bottom of the tank and the bubbles go to the surface, from where they are collected. Then, the recovered concentrate is dried and ready to be sold or to be processed in electrorefining plants that increase its purity levels.

This research focuses on the decision making process when integrating the following stages: drilling, blasting, crushing and grinding. Thus, the key resources are the explosives amount and energy consumption. Their impact in the overall operation can be analyzed observing the total costs and the comminution plant throughput. In the drilling stage, the blasting design can be easily modified and so, its parameters correspond to the main variables for the modeling process.

1.1.3. Operations Division

Mining companies manage their operations by dividing them into two independent divisions: mine and plant. The mine is in charge of the drilling and blasting processes and the plant is in charge of the size reduction and flotation stages. Each division has its own budget, goals, managers, supervisors and workers. The mine mission is to extract the material and deliver it to the processing plant at the minimum cost. On the other hand the plant objective is to generate as much element of interest as possible given the available ore delivered by the mine division at the minimum cost.

The plant defines a cutting grade which corresponds to the minimum percentage of the element of interest that must be present in each block of material for it to be sent to the plant. The mine division needs to follow the grade indications for the plant to achieve its production goals. The grade of the material sent to the plant must be within a specific grade range because the plant has high set-up costs. At the same time, the mine division has to achieve its own material movement goals, what considers ore sent to the plant and waste sent to the dump.

From a managerial point of view, this division allows the mining companies to balance the overall operation, keeping the mine and the plant goals aligned and following the long, medium and short term plans. Under this belief, the mine division always tries to send material with the requested grade. If not, they will need to send more low-grade material or extract more waste to find better grade blocks. In either way, the mine division will move more material than planned, increasing its costs and/or not achieving its production goals.

1.1.4. Economic Incentives

Both productive divisions, mine and plant, have production goals and its workers receive monetary bonuses upon achievement. The mine division workers incentives depend on the amount of material moved to the dump and the plant. On the other hand, the plant workers are rewarded based on the production levels of the element of interest. The bonuses in the mine and plant divisions are also subject to whether they operate within each division's budget or not. In theory this incentives should procure a lean and balanced operation.

Nevertheless, these economic incentives can lead to operational and economic inefficiencies, since each division workers will try to maximize their performance indices, even if by doing so they can generate a negative impact on the other division. If the mine workers are behind their material movement goals, they tend to send less quality (lower grade) material to the plant. Also, if they are expending more money than planned, they cut costs by reducing the amount of explosives load in each blast hole. That generates an increase in the particle size and so, an increase in the energy consumption in the comminution plant. Thus, the particle size increase reduces the haul and loading operations productivity and it dramatically increases the energy consumption in the crushing and grinding processes.

Under this circumstances, the plant operators face an increase in their costs and a reduction in the production levels. To meet their goals they ask the mine division to send higher grade material with a smaller particle size, in order to reduce the comminution costs. This generates a vicious cycle because the plant employees will keep asking for higher

grades and smaller sizes and the plant operators will keep sending coarse material because they are in an endless battle to get the economic incentives.

The current economic bonuses force each division to find their own production optimum, getting farther from the overall global optimum. If the decision-making process is carried out integrating both divisions, it is possible to reduce the total costs and achieve economies of scale. This happens because the cost increase in the blasting stage of the mine division can lead to great savings in the other.

1.1.5. Processes Integration

Following a Mine to Mill configuration, the mine and plant objectives are aligned and a global optimum can be found. Modifying the blasting design and increasing the amount of explosives load in the blast holes, can lead to a more efficient fragmentation process and so to smaller size particles. Even though, those changes will increase in the costs of the mine division, they will generate a large positive impact in the downstream comminution processes. The smaller particles need to undergo less times through the size reduction stages. This decreases the energy consumption, which is a key driver of the overall costs.

There are technical, operational and economical constraints when defining the amount of explosives (powder factor) and the blasting design used to fragment the in-situ ore. However, as this research will show, these decisions generate a drastic reduction in the energy consumption at the crushing and grinding processes, what reduces the costs and increases the annual revenues.

At the same time, it increases the comminution plant throughput which depending on the downstream process can increase the overall productivity. Another benefit of this approach can be observed in the load and transportation stages because the trucks can have a larger load factor, avoiding empty space in the load.

These operational changes generate an increase in the mining division costs and a reduction in the plant costs. As this research will show, a slight increase in the mining

division cost will generate a significant reduce in the plant division costs. Furthermore, under this setting the workers monetary incentives need to be reassigned. The bonuses should be assigned depending the productivity and costs of the whole operation and not by division. There is a trade off between the managerial benefits of the operations division and the reduction of the overall costs.

1.2. Objectives

The main objective of this research is to develop a mine to mill mathematical model of a copper open pit mine which can help us to study and analyze the impact of blasting decisions in the cost structure and energy consumption. In order to achieve this main objective we have defined three secondary objectives:

- (i) Study the existent mathematical models of the drilling, blasting, crushing and grinding processes and analyze which of the proposed modifications should be utilized to define if it is possible to integrate them in order to estimate the impacts of the blasting decisions in the downstream processes.
- (ii) Develop an integrated mine to mill mathematical model of a mining operation able to quantify the operational and economical impacts of any configuration to determine if there exists a trade-off between the blasting design and the energy consumption in an open pit mine.
- (iii) Simulate different blasting scenarios for a Chilean open pit copper mine to determine if there is a blasting design that maximizes the efficiency in the downstream processes and reduces the resources consumption.

1.3. Hypothesis

In order to achieve the proposed objectives we propose the following research hypothesis:

- (i) An adequate selection of blasting design variables, such as: powder factor, spacing, burden and diameter, will have a significant operational and economical effect on important mill parameters, such as: throughput and energy consumption.
- (ii) An increase in the explosives load (powder factor) and a variation in the blasting grid design has a direct effect on the reduction of the overall cost and energy consumption in the downstream processes.
- (iii) There is a blasting design that reduces the costs and energy consumption, increasing the throughput and annual revenues.

1.4. Thesis Outline

This thesis is based on the presentation of a paper that shows the main findings of the research. The thesis is organized as follows. Chapter 1 is an introductory section that presents the context and the main objectives of this work. Chapter 2 corresponds to the journal article written from this work. Finally, Chapter 3 contains the main conclusions of this work and suggests some further research around this topic.

2. MATHEMATICAL MODELLING OF BLASTING DECISIONS USING AN INTEGRATED OPEN PIT MINE TO MILL MODEL

In this paper, we develop a mathematical model that analyzes blasting decisions using an integrated open pit mine to mill model. Our mine to mill model is focused on the optimization of the blasting stage in order to determine the particle size that maximizes the efficiency of downstream processes. It is able to quantify the economic benefits of optimal blasting decisions by integrating the blasting, crushing, and grinding processes in a Mine to Mill configuration. Our model is based upon the integration of existing blasting and comminution mathematical models, which can simulate multiple scenarios of blasting designs and analyze their impact on plant throughput, energy consumption, and annual revenues. The models were calibrated using information from a copper mine located in the north of Chile. Results indicate that varying the key blasting parameters is associated with major increases in the plant throughput and the operation's annual revenues. Increments of 25% in plant throughput and annual revenues were observed with a 15% reduction in the blast diameter and a 15% increase in the powder factor.

2.1. Introduction

Prior research suggests that, in mining operations, blasting design and execution may be the most important step of the comminution process (McKee, 2013). Kanchibotla et al. (1998) quantifies that, for an open pit gold mine, an increment in the powder factor from 0.58 kg/m^3 to 0.66 kg/m^3 can cause a 12% drop in SAG milling energy consumption. Also, since blasting is the most energy-efficient stage of the comminution process, efficiencies of 15% to 30% can be obtained through adequate design and execution. This stands in contrast to grinding, which is approximately 2% efficient (Eloranta, 1997). Michaux and Djordjevic (2005) indicate that SAG mill performance is also influenced by the blasting practice and fragment strength. They argue that the post-blast residual fragment strength can significantly influence SAG Mill performance, producing up to a 20% increase in throughput. Finally, Scott et al. (2002) shows a potential increase of \$1 (\$1.1+) in net

revenue per run-of-mine, or ROM, tonne for an increase of 15% (30%) in the blasting intensity. All of these figures are a clear indication of the importance of optimal blast design and execution for the efficiency of downstream processes and the economic performance of mining companies. They suggest a need for an integrated mathematical model for blasting design and execution that can account for the different processes, variables, and interactions involved in the comminution process.

Improvements in the productivity of mine and mill processes can be achieved by focusing on three of their aspects: (i) maximizing the semi-autogenous (SAG) mill by providing it with the optimum feed size distribution; (ii) optimizing the blast fragmentation and muckpile profile to maximize the productivity of load and haul operations; and (iii) minimizing ore body dilution and high wall damage due to blasting (Grundstrom, Kanchibotla, Jankovich, Thornton, & Pacific, 2001). Another important economic aspect is operations costs. Studies by the US Department of Energy (DOE, 2007) have shown that comminution processes usually represent more than 44% of the total energy consumption of a mining operation (4% crushing and 40% grinding) and 21% of the total costs of mining supplies. Also, Tosun and Konak (2015) shows that the most important unit cost of open pit operations is the total energy consumption of the crushing operations, significantly surpassing the loading, hauling, drilling, and boulder crushing unit costs. Hence, any reduction in the energy consumed by these stages would decrease the total cost per processed tonnage.

As Scott et al. (1999) explains, a Mine to Mill optimization has two direct benefits. First, the increase in the proportion of fines produced after a redesigned blasting stage increases the mill throughput and reduces the energy consumption in the comminution processes, since the fine particles pass freely through the crushing and grinding stages. Second, the reduction in the top size of the blasted material improves the ease and productivity of the load and haul operations, as it allows the trucks to be fully loaded, avoiding empty spaces in the load.

Our contribution is the development of a mathematical model that explores the impact of the main blasting design decision, integrating it into a mine to mill model of the blasting,

crushing, and grinding processes. The model takes into account existing trade-offs between the amount of explosives, the blasting design, the energy consumed in the comminution processes, and the plant throughput, allowing the decision maker to determine the economic effects of such decisions. We apply our model to the case study of a Chilean open pit copper mine, simulating multiple scenarios of drilling and blasting designs and determining their impact on other mining processes, primarily those that consume a large amount of energy and money.

The paper is structured as follows. In the first section, we present a bibliographic review of the mathematical models used to model the blasting and grinding processes. In the second section, we combine these blasting and grinding models into an integrated mine-to-mill model, determining the economic benefits for the mine. We then apply the integrated model to data from a copper mine in the north of Chile and simulate the benefits of a Mine to Mill optimization. In the fourth section, we report and analyze the effects of this optimization, focusing on variations in throughput and revenues. Finally, we conclude and mention further potential questions that this line of research presents for the mining sector.

2.2. Bibliographic Review

Mine to Mill is an operating strategy for mining operations that aims to enhance the performance of mining and downstream processing activities (McKee, 2013). Two important parts of the Mine to Mill strategy are blast fragmentation and comminution models. Both seek to model the effects of different variables involved in each respective process on the reduction in the fragment size. The blasting stage has previously been modeled by utilizing mathematical models (Kanchibotla, Valery, & Morrell, 1999), employing software tools such as JKSimBlast (McKee, Chitombo, & Morrell, 1995), or carrying out experimental studies (Mwansa, Dance, Annandale, Kok, & Bisiaux, 2010). Comminution processes are typically described by using models created from a series of surveys of crushing and grinding circuits (Kanchibotla et al., 1998), or by using simulation software like JKSimMet

(Jankovic & Valery, 2002). These approaches allow the user to analyze the variations in the plant throughput and energy consumption of a specific blasting design. However, while these procedures analyze the variation of some key parameters, they leave aside their economic impact on the overall operation; in fact, Saavedra et al. (2006) explain that blasting is traditionally considered to be a cost that needs to be minimized, without taking into account that an increase in the throughput may increase the net present value of the operation despite the increase in costs.

Several studies have shown a positive impact of Mine to Mill optimization. For example, the Newmont Ahafo operation showed an improvement of at least 8% in total SAG mill throughput (Mwansa et al., 2010) compared to the benchmark surveys as well as previous audits. Moreover, Jankovic and Valery (2002) stated that throughput gains of 5-15% have been recorded and confirmed at operations that comminution plants operate with SAG mills, such as Highland Valley Copper (Canada), Minera Alumbrera (Argentina) and Cadia (Cadia Newcrest Mining in Australia) through implementation of Mine to Mill concepts. Furthermore, in the Porgera Gold mine, simulations showed an increase of 25% in the throughput after applying a modified blasting design (Kanchibotla et al., 1998).

During the 11th International Symposium on Rock Fragmentation by Blasting (2015), different authors presented studies about how an optimization of the drilling and blasting processes can generate a mill throughput improvement. Gaunt et al. (2015) explains the methodology behind the blasting optimization generated a 46% increase the mill throughput over the base scenario at Ban Houayxai mine (Laos). This was achieved by performing a series of empirical blast trials which included the modification of the bench geometry, blast patterns and highly controlled implementation. At the Gol-e-Gohar iron mine (Iran), a set of blasting trials showed that a positive variation of the powder factor can generate a 30% increase of the SAG mill throughput and a 21% decrease in its energy consumption (Hakami, Mansouri, Ebrahimi Farsangi, Dehghan, & Faramarzi, 2015). La Rosa et al. (2015) conducted an similar study in a copper-gold mine located in Peru (Cerro Corona). Using predictive models developed by Metso Process Technology and Innovation (PTI),

the SmartTag ore tracking technology and on-site trials of different blasting configurations, it was found a blasting design that yielded a 15% throughput increase at the mill.

A comprehensive monitoring of the blasting trials allowed each operation to understand the blast movements and implement a plan to minimize the adverse blast effects (Gaunt et al., 2015). The mentioned cases considered the utilization of image recognition software to adapt their blasting design to reduce the risk of dilution and wall damage. At the Ban Houayxai mine, wall damage was prevented using half the spacing in the final row of the production blast.

In this study, the blasting process will be mathematically modeled utilizing the Kuz-Ram model (Cunningham, 1983). It has suffered several modifications to achieve a better approximation of reality, as can be seen in Table 2.1. These modifications – the Crush Zone model (Kanchibotla et al., 1999), Raina et al.’s (2003) rock factor and Lopez-Jimeno’s energy factor (Jimeno, Jimino, & Carcedo, 1995) – will be explained in order to formulate a more complete mathematical model. The popularity of these models is due to a trade-off between their prediction accuracy and the inputs they require. Hence, these models are able to predict the outputs of the different mining stages without the necessity of calculating or estimating any complex parameters.

Table 2.1. Mathematical models used for each stage of the mining process

Stage	Model	Bibliographic Reference
Blasting	Kuz-Ram model	Cunningham (1983)
	Crush Zone model	Kanchibotla et al. (1999)
	Lopez-Jimeno’s energy factor	Jimeno et al. (1995)
	Raina et al.’s rock factor	Raina et al. (2003)
Crushing and Grinding	Whiten and White model	Whiten and White (1979)
	Bond’s equation	Bond (1952)

Kanchibotla et al. (1999) highlight that the Kuz-Ram model has been widely studied, which has allowed researchers to determine its failures. The greatest of these shortcomings is its underestimation of the fine particles produced by the blasting stage. One proposed

modification, the Crush Zone model, has been accepted as an effective remedy and used in several studies (Dey & Sen, 2003). The other limitations of the Kuz-Ram model include the imprecise determination of the rock and energy factors, which has been addressed by modifications developed by Raina et al. (2003) and Lopez-Jimeno (1995), respectively. In this paper, we will apply the mentioned modifications to an integrated model to increase its approximation of reality. As can be seen in Figure 2.1, incorporating the energy and rock factors generates a change in the blasting particle size distribution. These improvements increase the precision and objectiveness of the model's parameters and size predictions, as they are based on the Measurement While Drilling approach (Jimeno et al., 1995).

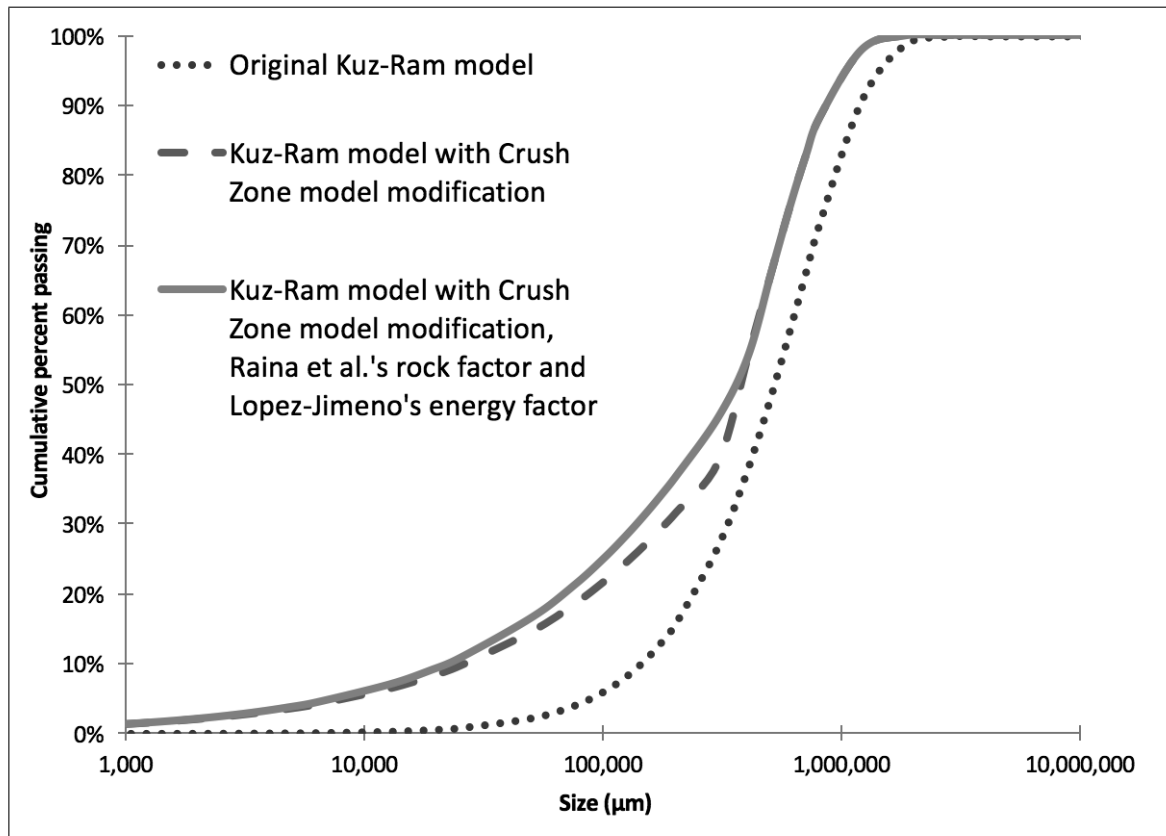


Figure 2.1. Particle size distribution under different approaches.

Then, we will explain the models that describe the comminution plant stages: the Whiten and White model for the primary crusher and the Bond's equation to estimate the energy consumption and throughput of the primary crusher, SAG and balls mills.

2.3. Modeling

To perform a Mine to Mill optimization, we first present the models that describe the processes occurring inside the mine, focusing on the blasting stage. To model the blasting stage, we present the Kuz-Ram model and the aforementioned modifications that improve its accuracy. Then, we detail the models that represent the stages of the comminution plant: crushing, classification, and energy consumption. After the models are presented, they are compiled into an integrated model.

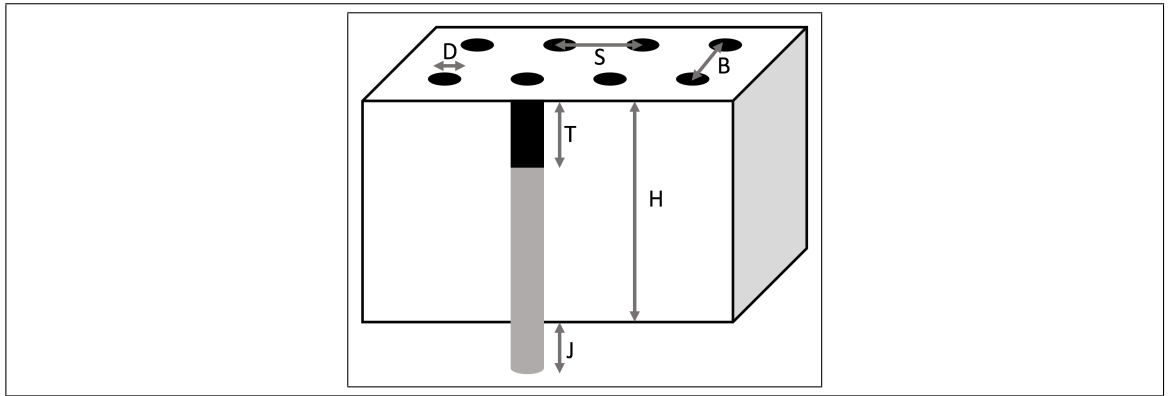


Figure 2.2. Blasting diagram.

2.3.1. Mine

The first step of the mining process, the drilling stage, corresponds to the definition of the blasting design; the key parameters that need to be determined are the burden, spacing, and blasthole diameter, as can be seen in Figure 2.2. On the other hand, the blasting process's purpose is to reduce the in-situ material size to make it transportable to the comminution plant, and its decisive inputs are the powder factor and the explosive sequence. In the following sections, we explain how to model the blasting stage and then analyze the impact of each parameter on the particle size distribution. First, we describe the Kuz-Ram model (with the Crush Zone modification). Then, we apply Lopez-Jimeno's energy factor and Raina et al.'s rock factor. A diagram of the modifications can be seen in Figure 2.3.

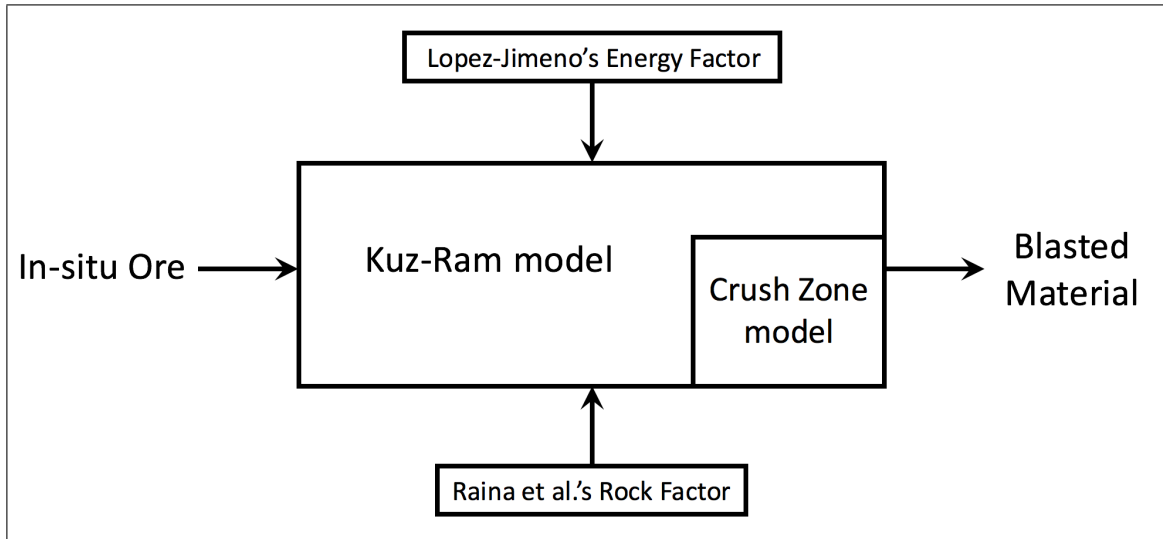


Figure 2.3. Blasting models diagram.

2.3.2. Comminution Plant

Three main processes occur inside the comminution plant: crushing, classification, and grinding. Primary crushing is the process in which the ROM material size is reduced in order to make it transportable and groundable. Classification is the process of testing particles by passing them through a screen; those that don't pass must be sent back to repeat the comminution process. Finally, grinding reduces particle size below $200\mu\text{m}$ to make particles floatable and recoverable.

2.3.2.1. Whiten and White model

The crushing process can be separated into two main stages: classification and breakage. Whiten and White (1979) developed a model for cone and jaw crushers, which assumes that the feed (\underline{f}), represented in a discrete form as a vector of its size distribution, passes through a classification stage $\underline{\underline{C}}$ (diagonal matrix), where the probability of breakage for each particle size is calculated. Smaller particles have a lower possibility of being crushed than bigger ones, which suffer many fractures. The particles that need to be crushed then go through the breakage stage $\underline{\underline{B}}$ (lower triangular matrix), where the distribution of the

broken particles into the size classes defined in the feed's vector occurs, originating the product \underline{p} (vector). A representation of this model (Nikolov, 2002) can be seen in Figure 2.4.

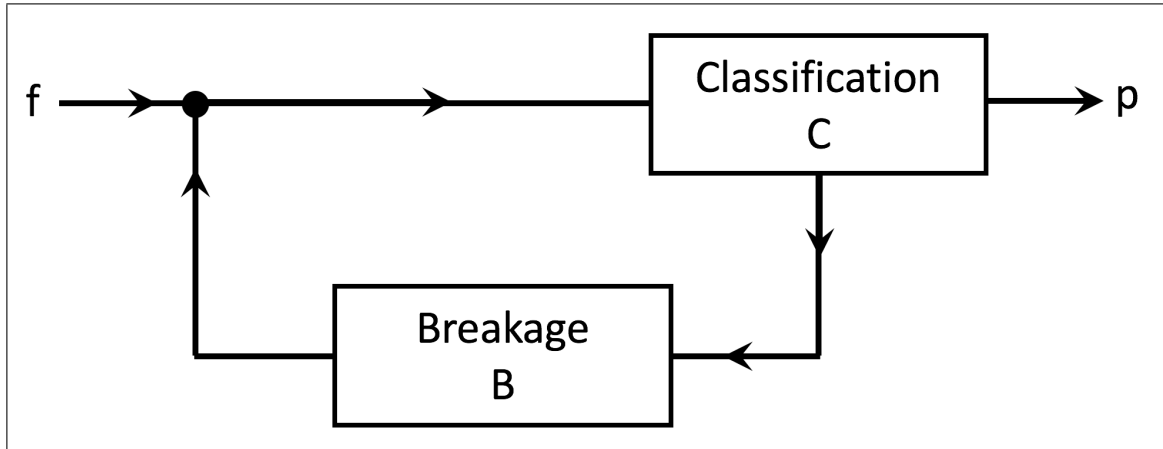


Figure 2.4. Scheme of the breakage process in a crusher.

2.4. Integrating Models

We propose a model that integrates blasting, crushing, and grinding. To do so, we use the classic models described in the previous sections, applying some modifications that increase the objectiveness of their parameters. In the next subsections, we explain every element of the model by stage, as well as the parameters required for each. As we explain above, the Mine to Mill approach centers on the optimization of the blasting stage to maximize its positive impact on downstream processes. Hence, the blasting variables that can be modified in the integrated model are the burden, spacing, blasthole diameter, and the powder factor. These variables are the main parameters of a blasting design. The integrated model is able to analyze the impact of any combination of these variables and the overall parameters, generating the following outputs: comminution plant throughput, energy consumption, and economic impact. Each output provides valuable information about the mining operation's performance. A summarized flowsheet of the model can be observed in Figure 2.5.

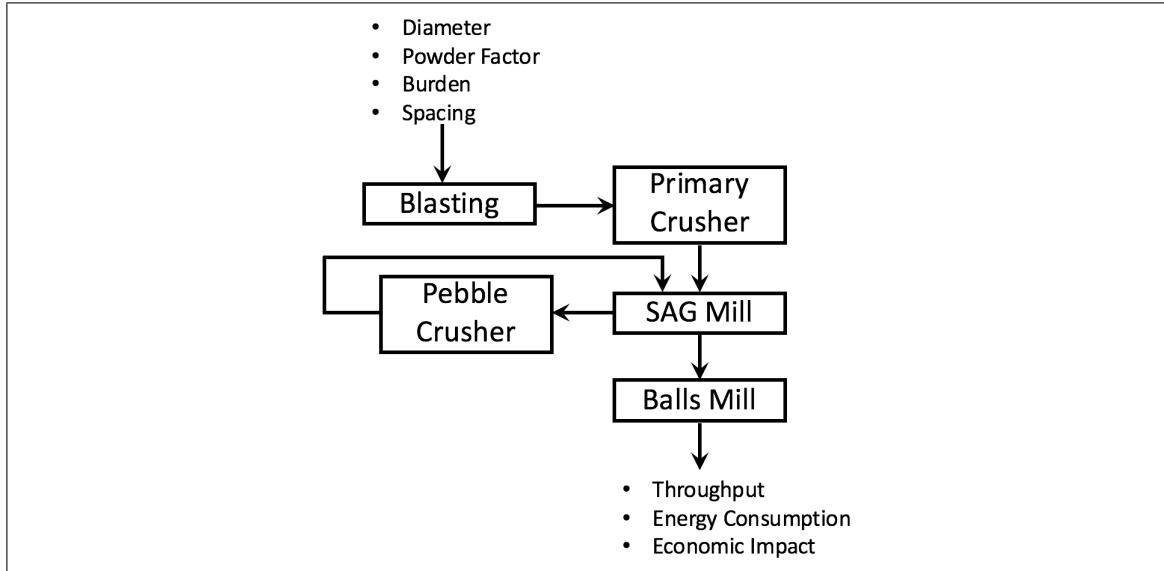


Figure 2.5. Integrated model flowsheet.

The integrated model allows for a fast and precise analysis of the performance of a mining operation for different configurations of the mine and plant parameters. Thus, it's possible to plot the global outputs of every simulation to determine which combination generates the best overall operational results.

2.4.1. Blasting

The blasting stage is simulated using the Kuz-Ram model with the Crush Zone modification; the latter allows us to avoid Kuz-Ram's underestimation of fines. The Drilling Index, proposed by Lopez-Jimeno, is utilized in the equations of Raina et al. (2003) and Jimeno et al. (1995) to objectively calculate the rock and energy factors, respectively. The information required by these models for their correct operation can be separated into three categories. First, we need the uniaxial compressive strength of the rock (UCS). Second, the models require several data points regarding the explosive used for blasting: its relative weight strength (E), density (ρ_{exp}), and velocity of detonation (VOD). On the other hand, the operational inputs are the blasthole diameter (D), bench height (H), burden (B), spacing (S), and total charge length (L). Finally, the required drill parameters are the standard

deviation of drilling accuracy (W), drill penetration rate (v_p), pull-down pressure on the bit, (e_p) and revolutions per minute of the drill bit (n_r).

After inputting these parameters, the blasting section of the model provides the particle size distribution that will be fed into the primary crusher.

2.4.2. Primary crushing

The (Whiten & White, 1979) model simulates the primary crushing stage. Its required inputs include the smallest particle size that undergoes breakage (γ_1), the largest particle size that can be found in the product (γ_2), a classification shape factor (γ_3), the mass fraction of the fine product (β_0), and two material coefficients (β_1 and β_2) that represent the shape factors for the fine and the coarse product size distributions, respectively.

These parameters can be obtained in two primary ways. First, as explained above, they can be determined from a regression analysis of a sample of material using particle size distribution values before and after the primary crushing process King (2012). Second, these input values are specific for each crusher and rock combination, so in the absence of particle size distribution values, they can be provided by the manufacturer of each crusher.

To estimate the energy consumed by the primary crusher (SEC_{pcr}) and its theoretical throughput ($tp_{h_{pcr}}$), we use Bond's equation; the parameters for this equation are the installed power of the primary crusher (pw_{pcr}), the rock's Work Index (W_i), and the size of the 80% passing of the product ($P_{80,pcr}$) and feed (F_{80}). To calculate the 80% passing size, it is necessary to determine the parameters of a Rosin-Rammler distribution through regression analysis of the particle size distribution from the Whiten and White (1979) model. These parameters are found by using MS Excel's Solver tool to minimize the total squared error between the Whiten and White (1979) particle size distribution and its Rosin-Rammler counterpart. This Rosin-Rammler distribution (equation 2.1) is separated into two curves to improve its fit to the Whiten and White (1979) model-generated curve,

where the first element corresponds to the prediction for the fines particles and the second one to the coarse ones. The equation is:

$$R = \delta \left(1 - e^{-\left(\frac{x}{x_f}\right)^{\eta_f}} \right) + (1 - \delta) \left(1 - e^{-\left(\frac{x}{x_c}\right)^{\eta_c}} \right) \quad (2.1)$$

where x_f and x_c correspond to the characteristic sizes of the fine and coarse particles, respectively, and η_f and η_c are the particles' shape factors.

2.4.3. Grinding

To predict the energy consumption and throughput of the SAG and ball mills, five parameters are required: the desired size of the 80% passing SAG product ($P_{80,sag}$), the desired size of the 80% passing balls mill product ($P_{80,balls}$), the SAG mill installed power (pw_{sag}), the balls mill installed power (pw_{balls}), and the balls mill recirculation rate (RR). The recirculation rate corresponds to the percentage of the SAG mill product that needs to be crushed again in the pebble crusher and depends on the crusher's product size ($P_{80,pcr}$). We propose an empirical approach that creates a constant (M) based on the base case primary crusher product ($P_{80,pcr,bc}$, μm) and the observed recirculation rate of the mine for the base case parameters (RR_{bc}). The constant and the recirculation rate for each primary crusher product (RR) can be calculated using equations 2.2 and 2.3.

$$M = \frac{RR_{bc}}{P_{80,pcr,bc}} \quad (2.2)$$

$$RR = M \cdot P_{80,pcr,bc} \quad (2.3)$$

$$tph_{peb} = \frac{tph_{pcr} * RR}{(1 - RR)} \quad (2.4)$$

The pebble crusher throughput (tph_{peb}) can be quantified using equation 2.4. With the 80% passing size of the primary crusher product ($P_{80,pcr}$), Bond's equation can be used to determine the specific energy consumption of the SAG and balls mills (SEC_{sag} and SEC_{balls}) and their theoretical throughput (tph_{sag} and tph_{balls}). It is important to note that the SAG mill throughput will always be conditional on the sum of the primary crusher and pebble crusher throughput ($tph_{pcr} + tph_{peb}$), and the balls mill throughput will depend on that of the SAG mill. None of the mills can process more ore than has been processed in the previous stage or more than the amount that it was designed to process. Hence, the plant throughput (tph_{pl}), as well as the SAG and balls mill throughput, will never exceed the minimum of the theoretical SAG, balls mill, and crusher throughput. Then, the plant utilization can be calculated by dividing the plant throughput into the theoretical value of the equipment (Kojovic, 2006).

2.4.4. Economic analysis

As explained by Hustrulid et al. (2013), the economic benefit of a block of ore (B_b , MMUS\$) is calculated using equation 2.5, where P_v corresponds to the metal price (US\$/lb), c_v is the selling cost (US\$/lb), Rec is the recovery fraction, and g is the average plant grade. c_{mine} considers the drilling, blasting, loading and hauling costs, and c_{plant} includes the costs of all the comminution and floating processes. If the extracted block is considered waste, the processing cost is removed from the equation.

$$B_b = [(P_v - c_v) \cdot 2204.6 \cdot g \cdot Rec - c_{mine} - c_{plant}] \quad (2.5)$$

We utilize an incomplete mining cost that only considers the drilling and blasting costs; we do so because other mining costs remain unchanged when modifying the blasting design. Also, the plant cost is calculated using only the cost of the energy consumed by the comminution plant, leaving aside other costs that are not affected by the blasting design, such as the workforce and the floating plant costs. Using equations 2.7 and 2.8, we can

calculate the costs per tonnage of material of the drilling and blasting processes (c_{db}) and of the comminution plant (c_{cp}).

$$N_{bh} = \frac{V_T}{V_0} \quad (2.6)$$

$$c_{db} = \frac{((H + J) \cdot N_{bh} \cdot c_{dr}) + (Q \cdot N_{bh} \cdot c_{ex})}{N_{bh} \cdot \rho_{rock} \cdot V_0} \quad (2.7)$$

$$c_{cp} = (SEC_{pcr} + SEC_{sag} + SEC_{balls}) \cdot P_{en} \quad (2.8)$$

where N_{bh} corresponds to the number of blastholes, V_T is the total volume that needs to be blasted (m^3), ρ_{rock} is the rock density (ton/m^3), c_{dr} is the drilling cost ($US\$/m$), c_{ex} is the explosives cost ($US\$/ton$ of explosives), and P_{en} is the price of energy ($US\$/KWh$).

Then, using equation 2.9, we can calculate the total tonnage processed by the comminution plant each year (tpy , MTon). Utilizing this value, the parameters mentioned above, and equation 2.10, we can estimate the annual revenue of the mine operation (Ben , MMUS\$). As mentioned above, our formula only considers the energy costs of the comminution plant and the drilling and blasting costs for the blocks of ore sent to the plant. This incomplete revenue formula allows us to compare potential revenues after a Mine to Mill optimization with base case revenues. This formula is sufficient because a Mine to Mill approach does not alter any of the other costs of a mining operation, and because a redesign of the blasting stage would not be applied to those sectors of the mine that are considered waste.

$$tpy = \frac{tph_{pl} \cdot 24 \cdot 365}{10^6} \quad (2.9)$$

$$Ben = [(P_v - c_v) \cdot 2204.6 \cdot g \cdot Rec - c_{cp} - c_{db}] \cdot tpy \quad (2.10)$$

2.4.5. Outputs

The comminution plant throughput represents the processing rate of the plant, which can also be used to calculate the comminution equipment's utilization. Any growth in the throughput will generate an increase in the amount of mineral processed in a given unit of time, which allows the plant to meet and even exceed its production goals. This will be reflected in an increase in the cash flows and hence in the NPV of the operation. On the other hand, calculating the utilization of the primary crusher, the SAG mill, and the balls mill allows us to analyze the mine status and assess operating options, like increasing, renewing, or updating mine and plant equipment. Thus, the comminution plant throughput is a key performance indicator for the entire operation when studying the impact of a Mine to Mill optimization (Ouchterlony, 2003).

In terms of plant throughput, a mining operation can face three potential scenarios. The first occurs when the primary crusher is the bottleneck of the operation, which implies that a redesigned blasting stage will produce a considerable increase in the overall throughput and the annual revenues. The second is that the SAG mill is the bottleneck, which suggests that the Mine to Mill optimization benefits will be mainly observed as a diminution of the energy required to reduce particle size, generating a tiny increment in the plant throughput. When the SAG and balls mill utilizations are at 100% and the primary crusher utilization is far below that value, operational decisions like installing another SAG or balls mill must be considered. The third option is that the balls mill is the operation's bottleneck, in which case the Mine to Mill benefits will be similar to those described for the second case.

When a Mine to Mill study is being analyzed, the energy consumption is able to show the impact and variation of the required energy to reduce the size of a tonnage of ore. As explained above, the idea behind a Mine to Mill optimization is to reduce the in-situ fragmentation size in order to increase the fine particles which pass freely through the comminution stages. Nevertheless, these smaller ROM particles generally only pass freely through the primary crusher, because the redesigned blasting stage is unable to produce a considerable amount of particles beneath the 200 μ m threshold. Thus, the primary crusher

product will remain largely unchanged, so the SAG and balls mills will keep working as usual from the grinding stage forward. Then, any diminution in the energy consumption will occur mainly in the crushers, a stage that only represents 4% of the total energy consumed by a mining operation, as detailed in DOE (2007). Taking this into consideration, we can conclude that overall specific energy consumption will not change significantly when a Mine to Mill optimization is carried out; in fact, it decreases by less than 1% for the studied cases.

To evaluate the economic impact of a redesigned blasting stage, the annual revenue of the operation is calculated using equation 2.10. As mentioned above, this equation only considers some of the drilling, blasting, and comminution costs, leaving aside those costs that are not affected by a Mine to Mill optimization. Also, it only considers the blocks of material that are processed in the plant. Then, after calculating the annual base case revenue, which corresponds to the current blasting design of the mining operation, a Mine to Mill study calculates the annual revenue for alternative blasting configurations. Annual revenues increase with comminution plant throughput, because more ore is processed and a larger amount of the element of interest is sold every year. Revenues for different combination of input variables can be easily computed and compared.

2.5. Integrated Model Implementation

We utilize VBA to compile all the mathematical models that describe the mining stages into an integrated Mine to Mill model. However, the user interface of the integrated model is a Microsoft Excel spreadsheet where one button needs to be clicked to get the optimal blasting decisions for any operational configuration. the user needs to input the operational parameters of the different mining processes in the same interface. Once the model has been executed, the Excel file displays the key performance indicators of the operation and the optimization results in a user friendly way as shown in figure 2.6). All the tables and charts present in this paper are automatically generated by the integrated model.

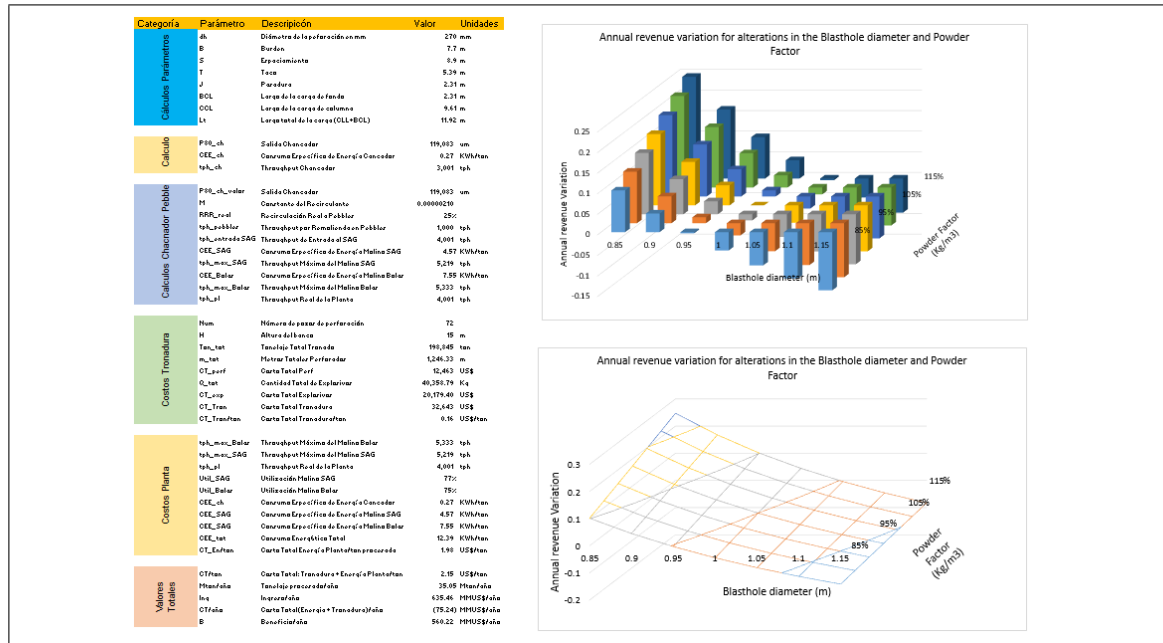


Figure 2.6. Integrated model outputs and KPIs sheet.

Due to the complexity of the different models, we utilize numerical methods to find the best blasting configuration. The integrated model iterates over different values of the key variables of the blasting stage. For some calculations, it performs minimum mean squared error procedures to increase the accuracy of the results.

With the VBA formulation, the integrated model can be operated as a big formula that yields the optimal operational conditions to maximize the company revenues, based on operational parameters and the blasting variables. The optimization is performed for any variation range of the key blasting variables. Nevertheless, for the purpose of this study the iteration over the key variables was limited to up to 15% variation over their base value used in the current operational scenario (85% to 15%).

The 15% limitation is used because this model does not account for potential negative impacts of redesigning the blasting grind and increasing the amount of explosives in each blast-hole. One of the negative impacts is high-wall damage caused by a ground vibrations, where blast waves transmitted through the ground can damage and impact the stability of the mine walls.

On the other hand, dilution represents another negative economical impact of pursuing a non-controlled explosion. It occurs when material with different grades gets mixed by mistake. Material meant to be processed in the plant might end in the dump, and material meant to be in the dump could be sent to the plant reducing the overall grade, and so the annual revenues.

To account for this negative impacts, operations have developed and utilized mathematical models that simulate wall damage caused by blast vibration. Furthermore, another approach has been to perform on-site blasting trials to calibrate predictions models and set lower and upper bound limits to the blasting variables. Gaunt et al. (2015) explains that it is required to understand the blast movement dynamics of each operation by performing a comprehensive blast monitoring and adjusting any prediction model specifically to each operation. Furthermore, as this study only uses operational information of a mine, the user should define variation bounds for the key blasting variables to avoid blast induced dilution and damage to the nearby walls. The user interface of the integrated model allows the the utilization of ranges for the blasting variables.

2.6. Results and Discussion

To validate the integrated model and demonstrate its utility, we will use parameters obtained from a Mine to Mill study for a copper mine located in the north of Chile, the name of which we cannot reveal at management's request. The rockmass, explosive properties and blasting design are very similar to those described in Kanchibotla et al. (1999)'s paper. The parameters of the primary crusher, SAG mill, and balls mill are in the same order of magnitude as those in Silva and Casali (2015). The economic parameters were provided by the mining company as referential values in order to perform an economic impact analysis of the optimization. The inputs required by the integrated model are shown in Table 2.2.

As mentioned above, the outputs of the integrated model are the comminution plant throughput, energy consumption, and economic impact. These outputs allow us to measure

Table 2.2. Integrated model inputs.

Rockmass properties	
Rock type	Andesita
Density (g/cm ³)	2.7
UCS (MPa)	150
Rock Factor	8
Drilling Index	1.25
Work Index (KWh/ton)	15.9
Blast design parameters	
Hole diameter (mm)	270
Bench Height (m)	15
Burden (m)	8
Spacing (m)	9
Total charge length	12
Explosive properties	
Explosive	Bulk ANFO
Density (g/cm ³)	0.78
Relative weight strength (%)	100
VOD (m/s)	5,000
Powder factor (Kg/m ³)*	0.55
Plant parameters	
Primary crusher CSS (mm)	100
Primary crusher power (KW)	800
SAG mill power (KW)	23,862
SAG mill $P_{80,sag}$ (μ m)	1,000
Recirculation Rate	25%
Balls mill power (KW)	2 x 20,134
Balls mill $P_{80,balls}$ (μ m)	160
Economic parameters	
Average plant grade	0.44%
Recovery fraction	89%
Drilling cost (US\$/m)	10
Explosive costs (US\$/ton)	900
Price of energy (US\$/KWh)	0.16
Metal price (US\$/lb)	2.5
Selling cost (US\$/lb)	0.4

*Unit of measure of Lopez-Jimeno's Powder Factor

the mine performance and make the right decisions to optimize the overall operation and maximize profits. The integrated model outputs for the base case are provided in Table 2.3. For the given data, the bottleneck of the operation is the primary crusher, which prevents

the SAG and balls mills from working at their maximum capacity. In fact, as can be seen in Table 2.3, the SAG mill and balls mill utilization rates are 76% and 74% respectively, and the plant throughput is 3,962 ton/h.

Table 2.3. Integrated model outputs.

Operational & Economic main outputs	
Primary crusher F_{80} (mm)	668
Primary crusher SEC (KWh/ton)	0.27
Primary crusher max throughput (ton/h)	2,972
Pebble crusher throughput (ton/h)	991
SAG mill SEC (KWh/ton)	4.57
SAG mill max throughput (ton/h)	5,222
Balls mill SEC (KWh/ton)	7.55
Balls mill max throughput (ton/h)	5,333
Plant throughput (ton/h)	3,962
Primary crusher utilization	100%
SAG mill utilization	76%
Balls mill utilization	74%
Annual revenue (MMUS\$/year)	552

To understand the impact of the modifications made to the Kuz-Ram model, which fix some of the issues that diminish its precision, the entire mining operation was simulated using various combinations of these blasting models (see Table 2.4). Each of these modifications generates a substantial impact on key operational and financial indicators, such as the plant throughput and the annual revenues. For example, when the blasting stage is simulated using the original Kuz-Ram model, the estimated annual revenues are 510 MMUS\$, 42 MMUS\$ less than in the case that considers all three modifications. This difference can be explained by the Kuz-Ram model's underestimation of fines, which produces an increase in the comminution plant costs because the material size is larger.

When we incorporate the Crush Zone model (without the corrections in the energy and rock factors), the estimated throughput is 3,570 ton/h and the annual revenues are 498 MMUS\$ - 392 ton/h and 54 MMUS\$ less than the base case. One reason for this variation is the reliance on an ideal energy factor, which is less than the real factor required

Table 2.4. Simulation outcomes for variations in the model utilized for the blasting stage.

Model Variations	Primary crusher F_{80} (μm)	Plant throughput (ton/h)	Annual revenue (MMUS\$ /year)
Original Kuz-Ram model	933	3,662	510
Kuz-Ram model with Lopez-Jimeno's energy factor	895	3,710	517
Kuz-Ram model with Raina et al.'s rock factor	697	4,008	559
Kuz-Ram model with Raina et al.'s rock factor and Lopez-Jimeno's energy factor	668	4,112	573
Kuz-Ram model with Crush Zone model modification	933	3,570	498
Kuz-Ram model with Crush Zone model modification, Raina et al.'s rock factor, and Lopez-Jimeno's energy factor	668	3,962	552

by the operation. Conversely, when the Kuz-Ram model is modified by the energy and rock factors, it overestimates the plant throughput by 150 ton/h and the annual revenues by 21 MMUS\$. Combining all three modifications is clearly beneficial: this is the only version of the model to accurately estimate the annual revenues of the mining operation. More precision in the information utilized by the model generates a better and more reliable decision-making process.

To carry out a Mine to Mill optimization, we analyze several combinations of the model inputs. We select these combinations by maintaining the base case values for two of the four inputs while modifying the remaining two according to a pattern. Specifically, the values for each of the modified variables are increased and reduced by 5%, 10% and 15%, generating 49 scenarios. Note that the powder factor depends on the blasthole diameter, as it is calculated using Lopez-Jimeno's energy factor. Thus, throughout the analysis, we use

the various powder factors proposed by Lopez-Jimeno for each diameter, adjusting them by the aforementioned percentages. The output tables or charts are presented only for those combinations of variables that yield a substantial change in output.

In the first scenario analyzed, the modifiable variables are the blasthole diameter and the powder factor; the burden and spacing remain at their base case values. In this scenario, the plant throughput and the annual revenue increase as the diameter decreases and the powder factor increases. In fact, when the diameter is at 85% of its base case value and the powder factor is at 115% of its base case value (for that diameter), the throughput increases by 25%, as can be seen in Table 2.5. Changes in annual revenue follow a similar pattern; for the combination mentioned above, revenue increases by 25%. The annual revenue variation can be observed in Figure 2.7.

Table 2.5. Plant throughput variation – modifying blasthole diameter and powder factor.

	K						
	85%	90%	95%	100%	105%	110%	115%
85%	10%	13%	15%	17%	20%	22%	25%
90%	5%	7%	9%	11%	13%	15%	17%
95%	0%	1%	3%	5%	7%	8%	10%
D 100%	-4%	-3%	-1%	0%	1%	3%	4%
105%	-8%	-7%	-6%	-4%	-3%	-2%	0%
110%	-11%	-10%	-9%	-8%	-7%	-6%	-5%
115%	-14%	-13%	-12%	-11%	-10%	-9%	-8%

When we modify the spacing and the diameter inputs, Table 2.6 shows that the throughput grows by as much as 19% when the diameter and spacing reach 85% and 115% of their base case values, respectively. For all modifications to the spacing and the diameter, the annual revenue varies almost as much as the plant processing rate. In the particular case described above, the annual revenues also increase by 19% (as compared to the base case).

Furthermore, when the diameter and the burden are reduced to 85% of their original values, the throughput grows by 21%, as can be seen in Figure 2.8. For that same case, the

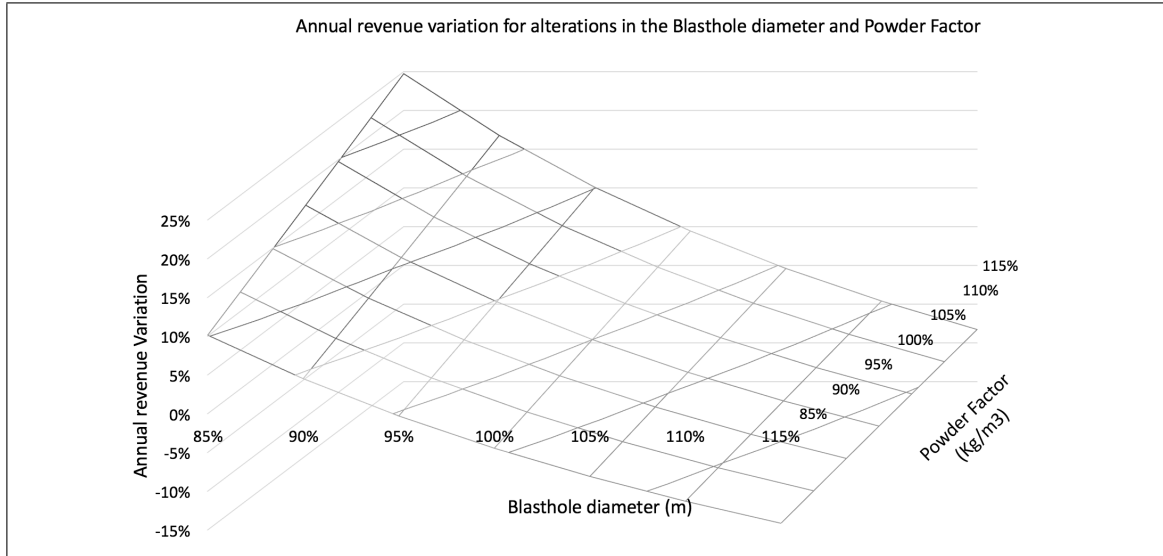


Figure 2.7. Annual revenue variation – modifying blasthole diameter and powder factor.

Table 2.6. Plant throughput variation – modifying blasthole diameter and spacing.

	S						
	85%	90%	95%	100%	105%	110%	115%
85%	15%	16%	17%	17%	18%	19%	19%
90%	9%	10%	10%	11%	11%	12%	12%
95%	3%	4%	4%	5%	5%	6%	6%
D 100%	-1%	-1%	0%	0%	0%	1%	1%
105%	-5%	-5%	-5%	-4%	-4%	-4%	-3%
110%	-9%	-9%	-8%	-8%	-8%	-7%	-7%
115%	-12%	-12%	-12%	-11%	-11%	-11%	-10%

annual revenue increases by 21%. In general, for this combination of modifiable variables, changes in annual revenue are 1% less than changes in plant throughput.

It is important to highlight that a redesigned blasting stage generates a reduction in the particle size distribution; in other words, it decreases the primary crusher F_{80} , or the maximum size of 80% of the material fed into the primary crusher. This indicator is commonly used to measure the whole particle size distribution, because it can be used as an input for Bond's equation to determine the energy consumed by comminution equipment.

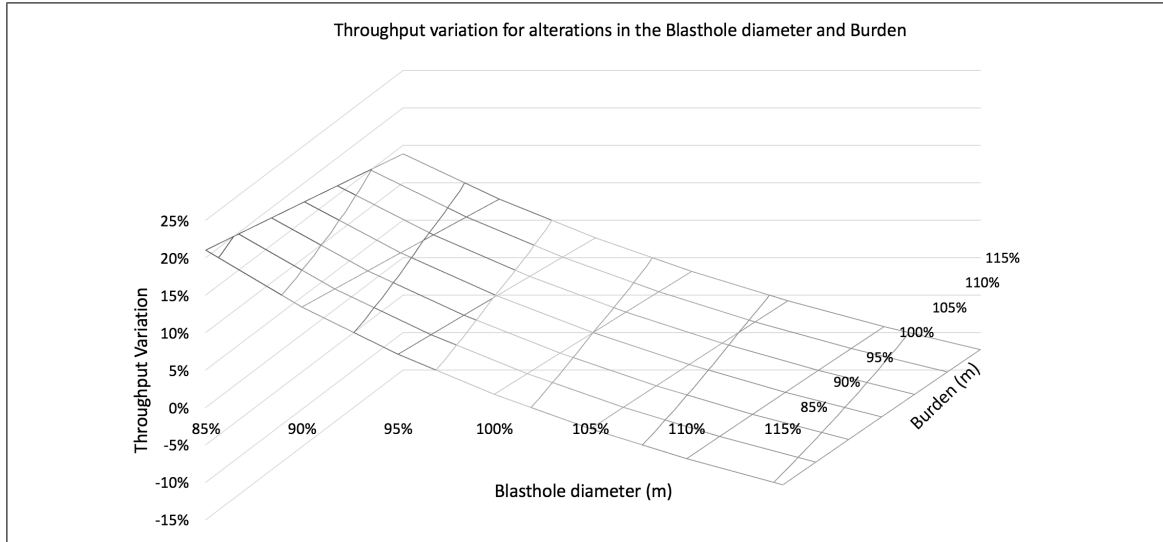


Figure 2.8. Plant throughput variation – modifying blasthole diameter and burden.

For the scenario in which the diameter and spacing were the modifiable values, the F_{80} variations can be observed in Table 2.7.

Table 2.7. Variation of the top size of the smaller 80% of the material feed into the primary crusher, for modifiable blasthole diameter and spacing.

	S						
	85%	90%	95%	100%	105%	110%	115%
85%	-28%	-28%	-29%	-29%	-30%	-30%	-31%
90%	-19%	-19%	-20%	-21%	-21%	-22%	-22%
95%	-9%	-10%	-10%	-11%	-12%	-12%	-13%
D 100%	2%	2%	1%	0%	-1%	-1%	-2%
105%	15%	14%	13%	12%	12%	11%	10%
110%	29%	28%	27%	26%	25%	24%	24%
115%	46%	44%	43%	42%	41%	40%	39%

As can be observed in the tables and charts, the optimum results are corner solutions which are bounded by the technical and geomechanical data of each mining operation and orebody. We also tested three other combinations of modifiable variables: powder factor and burden, powder factor and spacing, and burden and spacing. For each of these combinations, the positive variations in throughput and annual revenue never exceeded

6%, 6%, and 3%, respectively. In the first scenario, the throughput grew as the powder factor increased and the burden was reduced. In the second, the throughput increased when both modifiable variables were increased. In the final scenario, the annual revenue and the throughput increased as the spacing grew and the burden decreased.

The blasthole diameter has a major influence on the plant throughput and a similar impact on the annual revenues. It is important to remember that, following Lopez-Jimeno's equation, the diameter determines the powder factor, so the former shouldn't be changed without updating the latter. Thus, it can be said that the two inputs that generate the largest positive impact on the downstream processes are the blasthole diameter and the powder factor.

As mentioned above, another benefit of a Mine to Mill optimization is the increase in the efficiency and productivity of the load and hauling processes, because the reduction in the fragmentation size allows the trucks to be fully loaded, increasing the amount of material that they can transport. Additionally, redesigning the blasting stage produces more damage to the rock, generating micro cracks which weaken and soften the rockmass structure (Murr, Workman, Eloranta, & Katsabanis, 2015), reducing the energy required to ensure its breakage.

Despite all of its potential benefits, the Mine to Mill approach has not been widely implemented by mining companies. Some companies don't feel comfortable with the mathematical models used to simulate the optimization process, principally because some of these models are outdated and their shortcomings are well known (Ouchterlony, 2003). Nevertheless, during the last 20 years scientists all over the world have been developing more precise models that provide an accurate approximation of reality; we use these in our integrated model to simulate the stages of a mining operation.

Furthermore, while implementing a Mine to Mill study requires an immediate increase in the expenditures on the drilling and blasting processes, the economic impact on the overall operation takes several weeks or months to become apparent, because the blasted

material goes into a stockpile which operates according to a FIFO system. Hence, the blasting-optimized material will be processed in the mill only when all the material beneath it has been ground; thus it is required to be continuously monitoring every stage of a mine operation (Ouchterlony, 2003).

2.7. Conclusion

In this study, we aimed to create a precise integrated model of different mining processes, allowing us to perform an accurate Mine to Mill analysis. The integrated model combines several widely validated and up-to-date models to allow for easy, reliable exploration of multiple combinations of the key parameters of an open pit mine blasting stage in order to analyze the impact of an increase of the in-situ fragmentation on the downstream processes. The objective of our analysis was to find the combination of blasting inputs that maximizes the NPV, productivity, and efficiency of a mining operation. The integrated model can also be used for greenfield mining projects, allowing the user to create blasting designs and define the optimal comminution equipment.

The integration of multiple mathematical models allows for more precision in the simulation of the various mining stages, leading to better and more reliable information about the operation's performance. This increase in precision is also reflected in the estimation of the annual revenues, where a more accurate value enables a better decision-making process, especially for budget approval and investment decisions.

We determined that the variables with the largest influence on the performance of a mining operation are the blasthole diameter and the powder factor. The powder factor's importance is due to its link with the blasthole diameter in Lopez-Jimeno's equation and the Drilling Index, which is based on objective information about the rockmass. These results are aligned with prior literature, which indicates that the powder factor is the key variable in a Mine to Mill optimization.

An increase of 25% in the plant throughput and the annual revenues was observed for a reduction of 15% in the diameter and an increase of the same magnitude in the powder factor (15% increase over the updated powder factor calculated using the reduced diameter). Changing the blasthole diameter without updating the powder factor could negatively impact the mining operation's performance. The magnitude of this increment and the variation of the key variables is consistent with prior studies (Hakami et al., 2015).

The stages of a mining operation are usually broken down into two divisions for management purposes: mine and plant. To obtain the benefits of a redesigned blasting stage, the mining company must pursue the global optimum rather than the local optimum for each division. In other words, the increase in the drilling and blasting costs that accompanies a mine to mill optimization may prevent the mining division from achieving its costs and production goals. However, the performance of the operation as a whole would improve as both the plant throughput and the annual revenues grow.

Over the years scientists have proposed different methodologies and developed various models to perform a Mine to Mill analysis. These models provide different levels of accuracy based on the input parameters utilized. The integrated model proposed in this paper does not consider potential negative outcomes of a Mine to Mill optimization, such as dilution, high wall damage, and overloading the SAG and balls mills, which must be taken into account when designing or redesigning a blasting stage (Gaunt et al., 2015). Previous studies use two main approaches to include these impacts while optimizing the blasting design. One approach is to develop and utilize mathematical models that account for potential dilution and wall damage caused by blast vibration. The second one, is to perform on-site blasting trials to calibrate the model and set lower and upper bound limits to the blasting variables. With the current integrated model, the variation limits of each variable are up to the user and mine of study. The next step of this study will be to include mathematical models able to account for the blasting damage into a new integrated model.

3. GENERAL CONCLUSIONS AND FURTHER RESEARCH

We have developed and validate an integrated mine to mill mathematical model of an open pit mining operation using existent mathematical models of the different mining processes. Some of this models were created decades ago and so several modification have been proposed. We utilized those modifications that allowed us to create a model with simple inputs and outputs, but with enough precision to perform an accurate Mine to Mill analysis. The integrated model allows the user to simulate a mining operation and modify the four main parameters of a blasting design in order to analyze the impact of an increase of the in-situ fragmentation in the downstream processes. The objective of this analysis was to find the blasting design that improves the productivity of a mining operation while increasing the annual revenues.

The integrated model can be used for existing operations greenfield mining projects, allowing the user to create blasting designs and define the comminution equipment. The integration of multiple mathematical models and the consideration of some of the proposed modifications has led to to precise a simulation of the stages of a mining operation and to reliable indicators about the operation's performance. The precision increase is reflected in a more accurate estimation of the annual revenues. This enables a better decision making process specially when defining annual budgets or assessing possible investments.

The integrated model was calibrated by using operational and technical parameters of a Chilean open pit copper mine. The model was used to simulate the mining operation under different blasting design scenarios. The blasthole diameter and the powder factor (explosives load) were the variables with a major influence in the operation performance. These two variables are closely related because the model calculates the powder factor based on the blasthole diameter and objective information about the rockmass. These results are aligned with those present in the reviewed literature, which indicate that the powder factor is the key variable in a Mine to Mill optimization.

A reduction of 15% in the diameter and an increase of the same magnitude of the powder factor (for the reduced diameter) corresponds to the parameters combination that maximizes the mining operations revenues and efficiency. In fact, the simulation has shown that this parameters lead to an augment of 25% both in the plant throughput and the annual revenues. The magnitude of this increment follows the trend of the studies presented in the bibliographic review. The increase in the annual revenues is a consequence of an increase of the in-situ fragmentation that generates a reduction in the energy required in comminution stages. While performing the simulation it is possible to observe that the drilling and blasting cost correspond to a very small portion of the energy cost due to the size reduction stages. So, if there were no technical constraints, the optimal decision will be to increase the powder factor and reduce the blasthole diameter as much as possible.

As explained before, mining companies usually divide their operations into two independent divisions for management purposes: mine and plant. Each division has its own budget and goals, so it is important to understand and modify them before carrying out an optimization process through a Mine to Mill approach. The optimal scenario found by the simulation stage will lead to an increase in the mine division costs and a reduction in the plant division cost, meaning that the first one will not be able to achieve its cost goals. However, because under this configuration the mining company is pursuing the global optimum instead of the local optimum for each division, the operation performance must be analyzed as a whole. By doing so, the analysis will show that the plant throughput has increased and so the annual revenues. Following this idea, the workers economical incentives should be given based on the whole operation performance instead of just their division.

The current integrated model does not calculate upper and lower bounds for the blast design variables that can be modified when performing a Mine to Mill optimization. Further research is needed to determine the impact of the Mine to Mill approach over the dilution of the ore body. An increase in the powder factor will reduce the control of the explosion leading to undesired dilution between rocks with a high concentration of the element of

interest and waste. At the same time, a decrease in the explosion's control can generate wall damages risking the stability of the mine geomechanical structure.

Additional research should be carried out to study the effect of overloading grinding equipment due to a throughput increase of the crushing process. The bottleneck will be the grinding stage and so a blasting redesign might increase the complexity and rigidity of the operation, without a cost reduction.

Finally, the model can be expanded to consider all the mentioned elements and determine limits for the blasting stage key variables throughout the utilization of mathematical models. This will allow a maximization of the overall profit reducing risk of any negative outputs.

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