PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

ESCUELA DE INGENIERIA

A REAL OPTIONS APPLICATION TO MANAGE RISK RELATED TO INTRINSIC VARIABLES OF A MINE PLAN: A CASE STUDY ON CHUQUICAMATA U.G. PROJECT

MARIA FERNANDA DEL CASTILLO

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:
JOSÉ BOTÍN GONZÁLEZ

Santiago de Chile, Agosto, 2012

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Gratefully to my parents,

Maria Victoria and Raul.

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ABSTRACT

Traditional risk quantification methods provide little information on the sources of risk and tend to produce static over-conservative evaluations, which do not account for changes in the performance of the project. Capital investment decisions for large mining projects require of a more complex risk evaluation models, that includes the value of flexibility and the different risk levels associated with uncertainty on project variables (price, grade, dilution, production rates, among many other). In this context, Real Option Valuation (ROV) methods have proven potential to quantify the risk associated with such variables and integrate alternative scenarios and management strategies into the evaluation process. In this paper, a risk quantification model is developed, which successfully quantifies the risk associated to dilution, as a function of production rate. This model is then validated in a case study on the Chuquicamata Underground Mining Project.

RESUMEN

Los métodos tradicionales de cuantificación de riesgo proporcionan muy poca información sobre el origen del riesgo, y tienden a producir evaluaciones estáticas y sobre-conservadoras, que no tienen en cuenta los cambios que pueden producirse en el rendimiento económico del proyecto. Las decisiones de inversión en grandes proyectos mineros requieren modelos de evaluación de riesgo más complejo, que incluya el valor de la flexibilidad, y los distintos niveles de riesgo asociados a la incertidumbre en las variables del proyecto, como el precio, la ley del mineral, la dilución, la capacidad de producción, etc. En este contexto, los métodos de evaluación mediante Opciones Reales tienen probado potencial para cuantificar el riesgo asociado con dichas variables, e integrar en el proceso de evaluación el valor de escenarios alternativos y estrategias de gestión. En este estudio, se desarrolla un modelo de cuantificación de riesgo que logra cuantificar de forma exitosa el riesgo asociado a la dilución de una mina, como función del ritmo de producción. Este modelo es validado en un caso de estudio del Proyecto Chuquicamata Subterránea.

1. INTRODUCTION

Unlike any other industry, mining's "raw material" (ore), is not a commercial product for which the buyer knows the exact composition and properties, but rather a natural material, which chemical composition and physical properties are unknown and variable over the life of the mine. This fact explains why the orebody is, in most cases, the main source of risk in a mining business [54]. In mining, the grade, economic value and physical properties of the ore must be estimated from sampling, laboratory testing and expert judgment. As the result, the tonnage and the unit value of the resource inventory varies with the price of commodities and other market parameters. All these variability causes mining project's revenues to be dynamic rather than precise values, and because of this, both the downside and upside potential of a project need to be accounted for in its valuation and risk quantification [43].

Because of the uncertainty on ore inventory (reserves) and its variability with time, capital investment decisions cannot rely on a static parametric evaluation of expected cash flows, such as the discounted cash flow (DCF). This can only provide a static picture of project value associated to a "base case" scenario, on which managers must decide "green light", but fail to consider the dynamic character of decision making over the life of the project.

Conversely, Real Options Analysis (ROA) represents a better approximation to the way an investor see's a project: accepting that the future is uncertain, and that a good evaluation requires a thorough work identifying potential responses to the ranges of possible future conditions. This so called "future conditions" include internal (technical) as well as external (market) variability [2]. In general, an option - financial or real - is a right, but not an obligation, to perform an act for a certain cost, at or within a period of time. As so, options are able to add value as they provide opportunities to take advantage of uncertain situations, gaining from favorable scenarios, and hedging from downside risks [20], [31].

Current applications of the ROA focus mainly on external variables, such as commodity price, exchange rate, etc. which are controlled by external factors and cannot be engineered. However, the applicability in these “out of the project” area is fairly limited, and it has been widely studied, though not at all widely implemented.

This study focuses on analyzing the potential of RO valuation as a tool for quantifying and managing the risk associated to the variability of technical mine planning variables.

2. STATE OF THE ART - RISK QUANTIFICATION METHODS

Risk management may be defined as the act or practice of dealing with risk. This corresponds to a process or flow of actions comprising of: (i) Planning for Risk, (ii) Assessing risk issues, (iii) Developing risk handling strategies, and (iv) Monitoring risk to determine how they have changed. The goal of this process is to acquire a better understanding of the project’s possible outputs, in order to make the correct decisions, i.e. the decisions that maximize the project’s value.

Risk is associated to variables which present a relative uncertainty in their value, commonly but not necessarily related to the presence of partial information [54]. There are some types of risk (especially market risks), which cannot be eliminated by acquiring more information. This type of risks are related to a residual uncertainty, which is the risk that is left, when investing one more dollar in increasing the information results in less than a dollar on risk reduction. In other words, investing in more information may reduce risk, but actually eliminating it represents an excessively conservative approach which requires spending great amounts of capital, and doesn’t guarantee absolute results.

In a mining or industrial project, risk quantification refers to the process of estimating the expenditures required to eliminate (or reduce up to an acceptable level of confidentiality) the uncertainty associated to a given variable. This quantification represents a fundamental step in risk management, and it is a key phase in the process of decision-making under uncertainty. Quantification procedures may be classified into three approaches:

i) Expected Monetary Value (EMV)

ii) Expected Opportunity Loss (EOL)

iii) Expected Value of Perfect Information (EVPI)

Traditional risk valuation methods for mining projects fall into the EMV approach, where basically the value of the worst case scenario is used as point of comparison to quantify a given risk. EOL approach represents a quantification method that calculates the value of feasible alternative scenarios, and compares them with the base plan. Finally, as it was mentioned before, the EVPI approach corresponds to an excessively expensive and conservative approach, which is impossible to obtain in mining projects.

In this study, a variation of the EOL approach is proposed, using Real Options as the tool for analyzing the alternative scenarios. Here, a flexible system will be evaluated as point of comparison from the base case.

2.1. Traditional Risk Valuation Methods – EMV Approach

Traditional valuation methods correspond to static analysis of projects, where variables are considered fixed parameters, rather than uncertain values (such as the DCF valuation), and risk management is done based on completely uncertain variables, instead of risks with probabilities assigned to their possible values.

Traditional risk management strategies focus on designing a system capable of responding to all possible outcomes, trying to eliminate risk by creating expensive but safely robust operations that can defend themselves from various outcomes. However, there is actually only one final outcome, and correctly forecasting it is fairly impossible, especially in mining projects where a large number of variables (e.g. financial, metallurgical, geological, human, etc.), some of them interrelated, create a very complex scenario. As stated by De Neufville and Scholtes, 2011[17]:

"We have to recognize the inevitable uncertainty of any prediction and give up on the impossible task of trying to develop accurate forecasts of long term futures".

The resource business is about managing risk, not necessarily eliminating or minimizing it, since this could cause loosing valuable opportunities [43], [54]. In this line of thought, flexible designs don't provide the best results under all circumstances, but they do achieve lower cost, proactive systems capable of coping with a range of possible futures.

If variability is not accounted for, the most common approach to evaluation is to define a "mid-case", falling into the trap of the "flaw of averages", and considering risk as the worst case scenario, thus obtaining a consequent poor quantitative understanding of many tradeoffs between interacting variables [17], [60]. Conventionally, when dealing with static cash flow models, risk quantification methods are limited to scenario and sensitivity analyses [50], [56], [60]: the former by re-calculating project's performance under a number of alternative scenarios; the later simply varies one or more parameter to see the impact this has over the project's value, and from this, it supposedly defines the most representative variables.

However, even though the previous methods described deliver an indication of the project's NPV, they don't account for real uncertainty, as there is no guidance on the probability of occurrence of the variables being considered, nor do they provide any information on the variables' actual range of value.

2.2. Limitations of Traditional Valuation Methods

Traditional DCF valuation methods provide reliable results when flexibility options are not available, or when the project's uncertainty is limited and cash flows are fairly constant, but show great inconsistencies when parameters present variability. Several crucial limitations are described in the literature when referring to the conventional DCF valuation method, particularly when applied to mining projects. First, DCF assumes that all the analyzed variables are fixed parameters, not considering their stochastic reality [42]. A second limitation is that traditional DCF assumes that investment decisions are made "now or never", without considering the value of strategy and management [2], [9]. A third limitation is that the DCF method collapses all sources of risk into a single parameter: the discount rate, which is commonly shared among all the company's projects [42], [50]. As the result, DCF methods tend to undervalue projects by not considering management options and other scenarios alternative to the "base case" [30].

In fact, during the operational stage of a project, management has the capacity to react to the variations of extrinsic parameters, by making decisions which should aim to minimize negative outcomes and take advantage of positive scenarios. In many cases, future management reaction can be predicted and considered as real options at feasibility decision. Traditional DCF neglects the value added associated to future management reaction to change and therefore, it may lead to wrong feasibility decisions. Samis et al [49] states that the fundamental difference between DCF and ROV lays in how cash flow uncertainty on the project's value is accounted for. The challenge is to design a system that can cope with several futures by building enough flexibility into it, to allow management to adapt [17]. ROV provides the tools to do this: integrating flexibility into the initial model, thus increasing its reliability.

2.3. Real Options as a Solution – EOL Approach

Despite the general belief, Real Options Valuation (ROV) is not a substitute of the conventional discounted cash flow method (DCF), but rather a complement that fills the gaps that the DCF cannot address [28]. ROV uses DCF within a more sophisticated structure, capable of capturing the different options that exist on an investment project and the value associated to the possibility of management to react to change. In other words, ROV helps managers study the opportunities that will be presented in the future, being able to plan strategic investments upfront [2].

Real Options Analysis and Valuation methods (ROA/ROV) were created by acknowledging the similarities that exist between financial options derivatives and tangible investment projects; thus the name of “Real Options”.

2.4. Real Option Valuation

A key concept of options (real or financial) is that they are an asymmetric derivative; this means that to acquire an option, one must pay a premium upfront (i.e. buy the option), besides from the future expense that may be incurred in if the option is exercised. Flexibility is favorable but it’s not free, so the important thing to establish is how much the project’s owner is willing to pay today for an option, in order to increase flexibility and reduce risk in the future.

It must be stated however, that a flexible design permits but does not require expansion or change. The upside of these designs is that they recognize that uncertainty will reduce as the system develops, thus allowing for better judgment when making strategic decisions [17].

There are three known methodologies of option valuation resolution:

i. Partial Differential Equations,

ii. Binomial Models, and

iii. Simulation Models.

Partial Differential Equations include analytical, numerical and finite difference calculations. The core of this method’s resolution is that it equals the change in the option’s value to the change in value of a reference financial portfolio [2]. The most known analytical valuation model is the Black & Scholes formula (1973), developed to solve European call options. However, these models are not really applicable for valuing real investment projects, as the conditions needed for the formula to actually apply are at most, ideal.

Binomial models are widely used, as they are flexible and easy to understand. Besides, their diagrammed evolution is similar to a cash flow, so the decisions made upon them tend to be very transparent. However, in binomial trees the level of complexity grows exponentially with the number of uncertainties being considered, and so, their range of use is limited.

Finally, Simulation Models, with the most common being Monte Carlo simulation, in contrast with the previous valuation methods, enables the analysis of an endless number of variables, as the software developed for this purpose is vast and quite sophisticated. It can simulate European (fixed exercise time) as well as American (free exercise time) options, and it allows the valuation of complex problems without the need of over simplified unrealistic assumptions.

2.5. From Options ON Projects, to Options IN Projects

Until recently, all ROV applications had focused on market risks and uncertainties, where they have proven to be a very useful valuation method. In this aspect, real options have been widely studied, and thus, the scope for innovative work on this topic line is limited.

It’s important to notice that real options are not limited to market changes, but can also be used to evaluate internal, tactical uncertainties that affect the project. Wang and de Neufville [58] define the concept of options “on” projects, as the options that analyze variables that act upon the project (external conditions), and options “in” projects, as options that have the potential to actually change the design of the technical system. In other words, options that work upon the engineering variables, technology uncertainties ant technical risks of the system.

Kazakidis and Scoble [26] state that flexibility needs to be built into the project to not only act as insurance against adverse scenarios, but also to enable managers to take advantage of opportunities that may develop during the life cycle of the operation. Following this line of thought, real options' application in mining projects have matured into "mixed" views, focused on market uncertainties, but also acknowledging, as an "in" project's starting point, the mine's geological uncertainty.

Internal variables related to the geology of the orebody were first studied by Dimitrakopoulos, Farelly and Godoy [20] in year 2002, by using conditional simulation to develop mile planning options that integrate geological uncertainties into the valuation model. In this research line, some authors have now applied "in project" ROV to evaluate compound risk from extrinsic and intrinsic variables. Dimitrakopoulos, Martines and Ramazan [20] modeled price and geological uncertainties together in order to account for the risk associated to grade uncertainty when evaluating a project. Here, the authors decide from the simulation results by defining a "minimum acceptable return" on investment, and the option is valued as the range between the downside risk insurance, and the upside potential advantage. Musingwini, Minnitt and Woodhall [38] refer to a "flexibility index (FI)" defined by Kazakidis and Scoble [26], that represents the option's impact over the system, and apply it to a production flexibility option. This is done by managing ore availability, i.e. the amount of free face required not only to meet production, but to acquire "technical flexibility" (FI>1). All this applied to a South African underground reef mine, located in the Bushveld Complex.

Dimitrakopoulos and Sabour [19] studied an operational flexibility option including price and geological uncertainties, and use ROV and DCF for valuing an actual mine that in real life has already been extracted. Their study shows that the ROV design is about 15% higher than the DCF. Sabour, Dimitrakopoulos and Kumral [44] apply Monte Carlo simulation and Whittle pit design optimizer software to develop a method to rank the simulated mine designs. Akbari et al [1] include the same uncertain variables in their model, but also acknowledge that reserves are not only uncertain due to lack of exploration, but because they are dependant of price (due to cut off changes). Here, the author uses a binomial tree to simulate the metal price, and defines the optimal starting point of the mine, and the ultimate pit limit (dependant of "today's" price). Li and Knights [29] innovate and apply real options analysis into short term mine planning, by managing haulage routes to two different dumps, dependant of fuel price, which is also modeled as a mean reverting process of a geometric Brownian motion.

Although the applicability of ROV "in the project" have great potential, reference on the subject are scarce. A relevant example is Kazakidis and Scoble [26], where three "in the project" option scenarios on ground-related problems are studied: first, a sequencing option for increasing the flexibility of the production plan; second the option of hiring extra rehabilitation crew to deal with ground-related problems; and third, a trade-off study between different flexible alternatives in order to optimize the mine plan. The decision is made by using two parameters: first, the same flexibility index as in [38] and the capital cost of each option (the option's price). This is a very good example of real option's applications "in" projects, but here, the focus is placed on increasing project flexibility rather than managing or quantifying its risk, which is the focus in the present study.

3. RISK MANAGEMENT MODEL

One of the goals of this study is to demonstrate the potential of real options analysis to quantify and manage the risk associated to a mining project. This is, studying uncertain scenarios of feasible technical solutions, and including them as the project's new flexibility, in the design and valuation processes.

Risk results from the uncertainties present in the project, these uncertainties can create value and opportunities, but to do so, they first must be identified and characterized. Some uncertainties may be reduced by investing in more and better information, like paying for more drill holes in order to have a better knowledge of the orebody. However, for some project variables, such as commodity price, the level of uncertainty cannot be reduced following that strategy.

In this context, flexibility has proven to be the best way of managing risk; this means investing in a flexible design, that is capable of meeting the project requirements for a range of possible future values. Real options philosophy proves to be a powerful tool to manage risk through implementing flexibility in the design. However, not all types of risks may be managed by this method.

Botín et al [5] presents a classification of the risks present in an investment project, which consists in four groups, differentiated depending on their probability of occurrence and on the impact of the events. The categories are: fatal flaws, manageable risks, catastrophic risks and bearable risks. The graphical representation is shown in Figure 1.

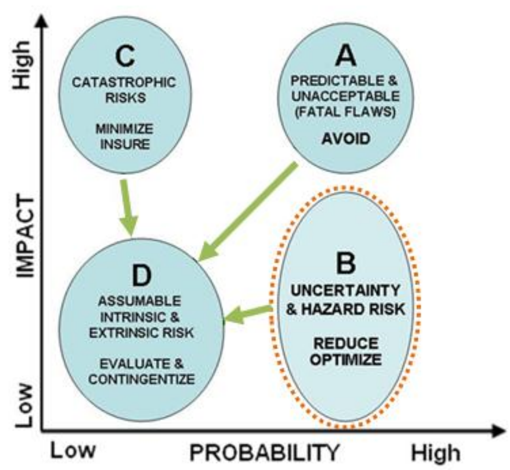

Figure 1: Risk Classification Matrix

Using this classification, a risk management flow model has been developed and is shown in Figure 2. Its goal is to define the actions that must be taken to evaluate each type of risks. According to this flow chart, risks A and C must be taken into account by a change in the basic engineering of the project, as they must be prevented at all cost (this action is especially focused on type "A" risks, which require a thorough revision of all possible project outcomes). At the opposite end are type D risks, where the cost of managing them is higher than the maximum possible gain obtained by eliminating them, and thus, they must be accepted as “bearable” (or “bankable”), and are not considered in the analysis.

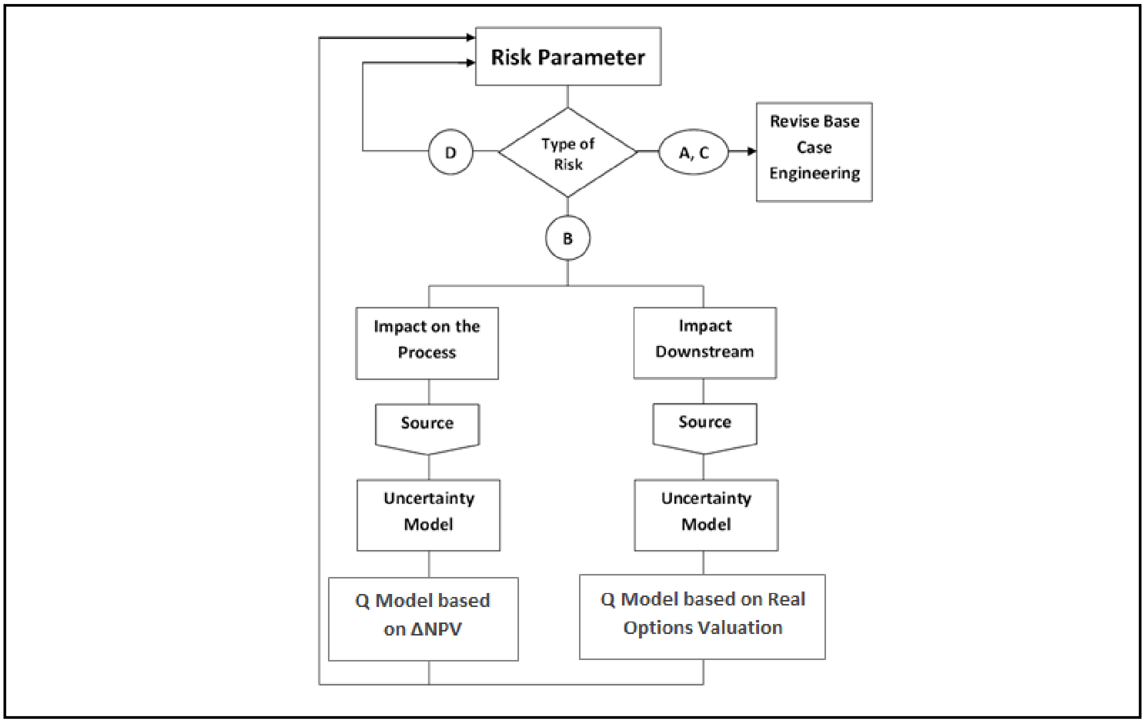

Figure 2: Risk Managements flow chart

Anyhow, the scope of this study focuses only on type B risks, particularly on technical risks that may affect the project at prefeasibility stages, and stay latent along the project cycle, from early exploration to mine closure. These risks are associated to variables that have an effect over the project’s value, but can be controlled and managed through different measures.

Type B risks can be subdivided into two classes: on one hand, risk related to variables whose impact is limited to one process, within the value chain presented in Figure 3, but do not have an effect in downstream processes. For example ore hardness, where the higher the hardness, the lower is grinding performance and the higher energy consumption, thus, reducing milling rates and cost, reducing project’s NPV. However, this impact may be managed within the process by investing in a larger mill and thus risk may be quantified on the difference of NPV between reality and the alternative without risk (left flow of Figure 2). The second type of risk (see flow chart), is the one associated to variables that do have an impact on downstream processes, for example ore grade and dilution. In this case, a decrease in ore grade estimation during the ore body evaluation stage, as well as an increase in dilution, have an impact on the amount of metal extracted, processed and produced, affecting all the project's whole life cycle. As shown in Figure 2, these types of risks may be considered as "un-eliminable", and thus can be evaluated and managed by using real options analysis, as different scenarios should be analyzed to define the final model. In this case, the project's value corresponds to a function of the values obtained by the different options considered, defining scenarios and their probability of occurrence, according to the variable's possible behaviors.

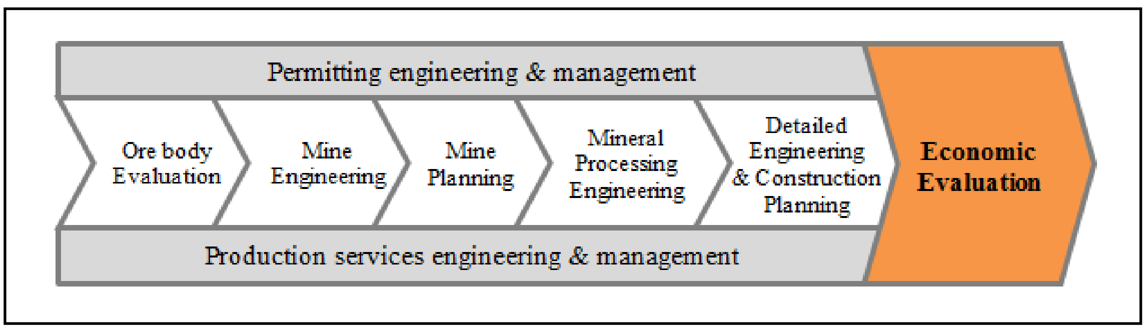

Figure 3: Mining Project's life cycle

4. CASE STUDY

4.1. CONTEXTUALIZATION

The risk in a Mine Plan results from the uncertainties on the value of some critical variables, such as ore grade, dilution, efficiency, performance, metal price, etc. The goal of this Case Study is to develop a RO model to estimate the risk derived from the uncertainty on the value of grade dilution. The proposed model combines ROV and

Monte Carlo simulation of the project's life cycle, to monitor the results of the handling strategies. It is worth noting that this ROV model will stay independent from external variables (market conditions), focusing solely on this internal/technical variable: mine dilution, and thus extending RO's common applicability.

Dilution is a key variable in most mining projects. Its value depends on the mining method, the geometry and regularity of the orebody, the rock quality, etc. and in some cases may reach values as high as 50%. In a mine plan, grade, ore recovery, dilution and production performance are assumed constant in the planning model. In this context, ROA will be used to evaluate the risk related to the actual uncertainty on the value of dilution. Although ROV can be applied to many other internal and external variables, the scope of this case study is bounded, focusing only on dilution: a high impact technical variable that, when underestimated, may cause significant production losses.

4.2. Base Case

The case study analyzes the Chuquicamata Underground Mine Project, owned by Codelco, the Chilean Company of Copper. The mine, located 16km north from Calama, Chile, has been operating by opencast mining since 1915. However, due to the increasing transportation costs and strip ratios, is now planning to go underground, as a block caving operation.

The orebody is a porphyry copper with an average grade of 0.71% Copper and 310ppm Molybdenum, and the mineable reserves amount to 1.7 billion tons of ore. The project is based on a production rate of 140ktpd, for a mine life of 40 years, which makes this project one of the largest underground operations in the world (see Appendix A for details).

The mining method selected is "Macro-Block Panel Caving". The mine layout is based in 4 extraction panels of approximately 250m high and 60 Ha of undercut surface area. Each panel is subdivided into approximately 20 "macro-blocks", of around 120m by 300m each. The mining sequence proceeds from the top panel downwards and from the center of each panel outwards along the West Fault. The caving of each panel is planned to overlap with the panel below as required by overall ground stability.

A sketch of this mine design is presented in Figure 4.

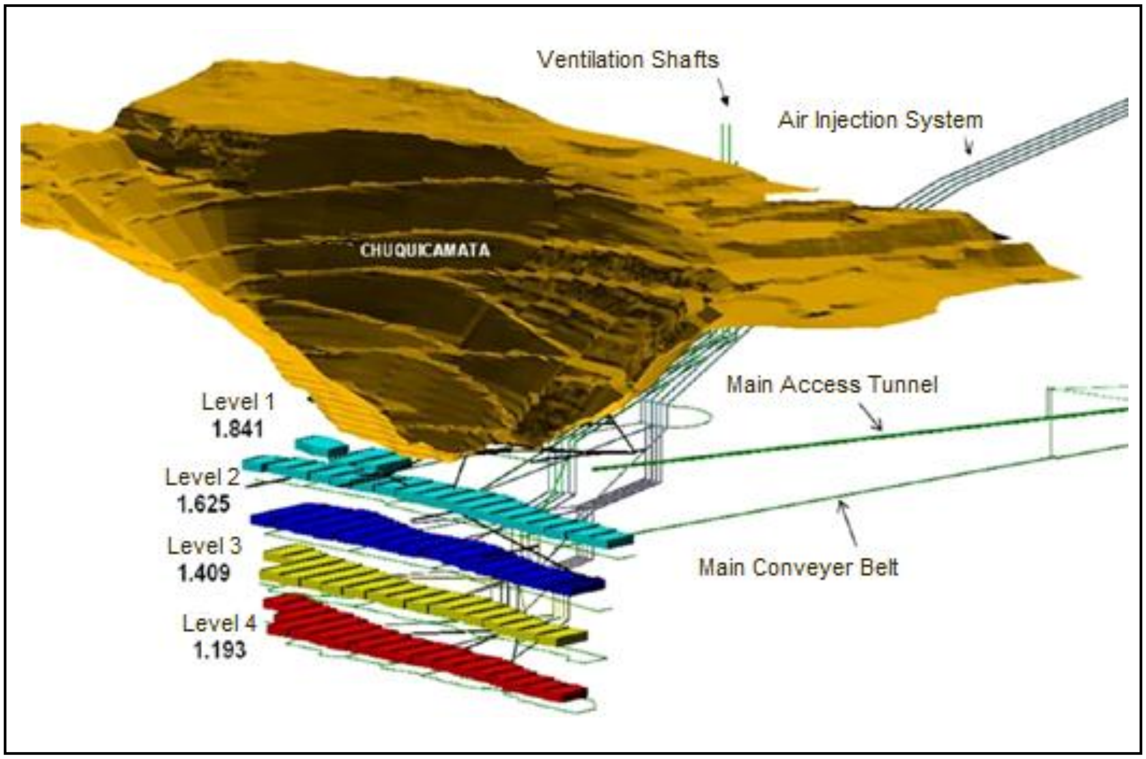

Figure 4: Chuquicamata Mine Design and General Layout

One of the most important aspects in this mining method is the control of dilution. Caving methods rely on gravitational forces for rock fragmentation and flow and thus, the control over this process is rather limited. There are several methods that have been developed to estimate dilution in block caving, but anyhow, the resultant level of uncertainty is considerably high.

At present, the project is in its early stages of development and production. Start-up is scheduled for 2019, with a ramp-up period of 6 years, a ramp-down period of 5 years, and 29 years of steady production at maximum capacity [41]. The operational and capitalcost data as well as all other base case assumptions provided by Codelco and are summarized in Table 1. Details are available in Appendixes B and C.

Table 1: Data assumptions

Market variables	*Unit*	*Cu*	*Mo*
Price	US$/tf	5 517	28 200
Payable metal	%	96.6%	97.3%
Treatment Costs	US$/tdm	-196	-980
Refinement Costs	US$/tf	-331	-1 380
Distribution Costs	US$/thm	-89	-109
Net Smelter Return	US$/tf	4 177	23 853
Discount Rate	%	8%	
Technical variables	*Unit*	*Cu*	*Mo*
Cut-off grade	%	0.430%	-
Ore average grade	%	0.711%	0.031%
Diluting rock grade	%	0.100%	0.002%
Extraction levels	unit	4	
Dilution (1st level)	%	12.5%	
Dilution (other levels)	%	15.0%	
Mining Recovery	%	83.0%	
Extractable Reserves	kton	1 760 000	
Production Rate	ktpa	50 400	
Metallurgical variables	*Unit*	*Cu*	*Mo*
Humidity	%	8.50%	
Metallurgical Recovery	%	86.35%	64.92%
Concentrate grade	%	50.00%	32.19%

Considering the previous information, an annual cash flow was developed; a summary of this cash flow is shown on Table 2. This valuation will be used as a starting point to compare the options that will be developed further on.

The “Operation” values shown in Table 2 correspond to the average values for the 29 years of steady operation at maximum capacity. The ramp-up and ramp-down flows are presented in the extended cash flow, which is available in Appendix E.

Table 2: Base Case Cash Flow summary

	Unit	Operation
Period	**year**	7 - 35
Ore ROM	**Mtpa**	50.4
Cu Con.	**Ktpa**	942
Mo Con.	**Ktpa**	34
OPEX	**MUS$**	548
TAX 57%	**MUS$**	378
CAPEX	**MUS$**	85
Cash Flow	**MUS$**	343

4.3. Risk from Dilution

The economic impact - risk - of a greater than expected dilution relates to the reduction of mill feed grade (ROM grade), and the corresponding reduction of concentrate production. Therefore, the risk management strategy would be to implement flexibility by designing the mining and mineral processing systems with a higher production capacity, capable of processing the extra waste rock resulting from higher dilution, so that copper production rates may be sustained when dilution is higher than the expected 12.5% (Base case). In other words, a production system capable of maintaining copper production rates at maximum dilution value should be considered as a “dilution risk-free option”. And to valuate this flexible risk-free system, ROV will be used.

As it was explained, extra flexibility means extra costs, both capital and operational. The extra CAPEX results from the additional capital investment in equipment and infrastructure required for a larger production capacity; the extra operating cost (OPEX) results from the increase of variable operating costs, such as power, materials, spare parts, fuel, etc. Resembling this cost structure to the option derivatives, the CAPEX corresponds to the premium paid up front to “buy” the option of flexibility, and the OPEX represents the exercise cost, that must be paid only if the option is applied.

4.4. COST OF FLEXIBILITY

To calculate the extra capital cost associated to a higher production rate, the William's model is used. This model is based in the cost relationship that exists between two plants or equipment of different capacity, power or volume, but of similar characteristics. It establishes the following relation:

$$C_A = C_B \left(\frac{Q_A}{Q_B}\right)^m \tag{1}$$

Where:

C_A ; C_B = Capital expenditures of plants A and B

Q_A; Q_B = Production capacity of plants A and B

m = Williams' exponent

In this case, Williams' model is applied to evaluate the cost of a capacity expansion of the mining and processing systems. In other words, plant A corresponds to the system with increased production capacity, and plant B corresponds to the original system, with the Base Case capacity of 140ktpd. Williams' exponent " m " depends on the investment's volatility and the presence of economies of scale, and varies by equipment, plant's process and industry [37]. Mining process plants are commonly evaluated with an exponent of 0.8, however, as complete mining operations tend to be more variable, an exponent of 0.7 is used.

As a cost estimating method, Williams' model is only valid for an "order of magnitude estimate". However, when used to estimate the CAPEX for the same system, at two different production rates, it provides the necessary accuracy. This way, for this case study, the Williams formula may be expressed in a simplified form as:

$$C_A = C_B \cdot (1 + r)^m \tag{2}$$

Where r = plant’s expansion weight factor.

Now, the main difficulty of this quantification is to determine the appropriate weight factor, that hedges the project from the risk derived from uncertainty on dilution, without over dimensioning the operation. To do this, we first must understand how the dilution will behave once the mine is being exploited; this is explained in the following chapter.

4.5. Modeling Dilution in Block Caving

4.5.1. Base Case Vertical Dilution

As mentioned before, caving methods are characterized by having a low control over waste dilution. Once a block is in production, there is no way to determine the volume of influence of a draw point, nor the dynamics of the rock mass flow.

Several draw models have been developed to simulate the ore-waste mixing process, which relate draw dynamics with rock quality and geology of the orebody [10]. Figure 5 shows the process that must be followed to obtain the extractable block-model. In this case study for the fourth stage of this flow, the volumetric mixing process model developed by D. Laubscher was used [17], [23].

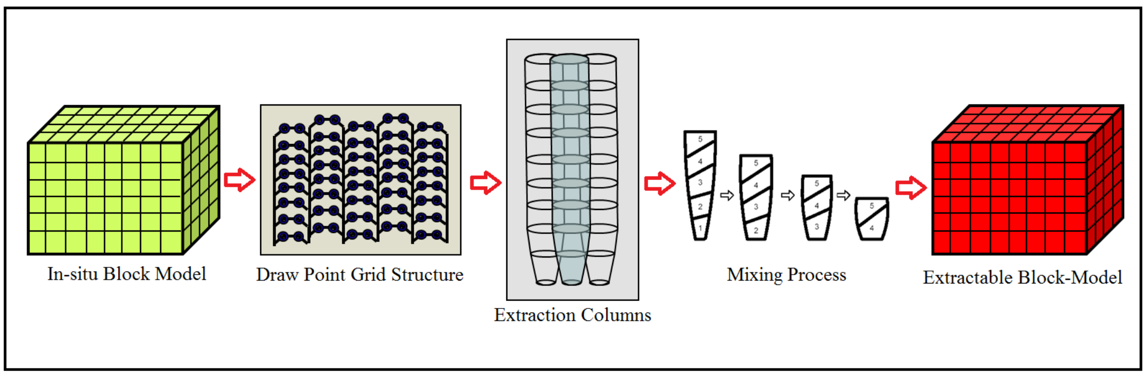

Figure 5: Block-Model mixing simulation process

The Laubscher model is based in one parameter, the PDE (percentage of dilution entrance), that represents the percentage of the column’s height that must be drawn before waste material starts to flow into the draw point. In theory, the PDE represents the velocity at which the particles mix inside a column. Figure 6 shows a column before and after mixing (horizontal lines represent the original model, and the red diagonal lines show the movement of particles after mixing). The bottom “slice”, represented in yellow, shows that a portion of the two slices above have occupied the original volume of the bottom slice, and the fourth “slice”, in blue, illustrates how at a given column height the mixing is such that the original mineral is just a fraction of the content of the slice that will actually be extracted.

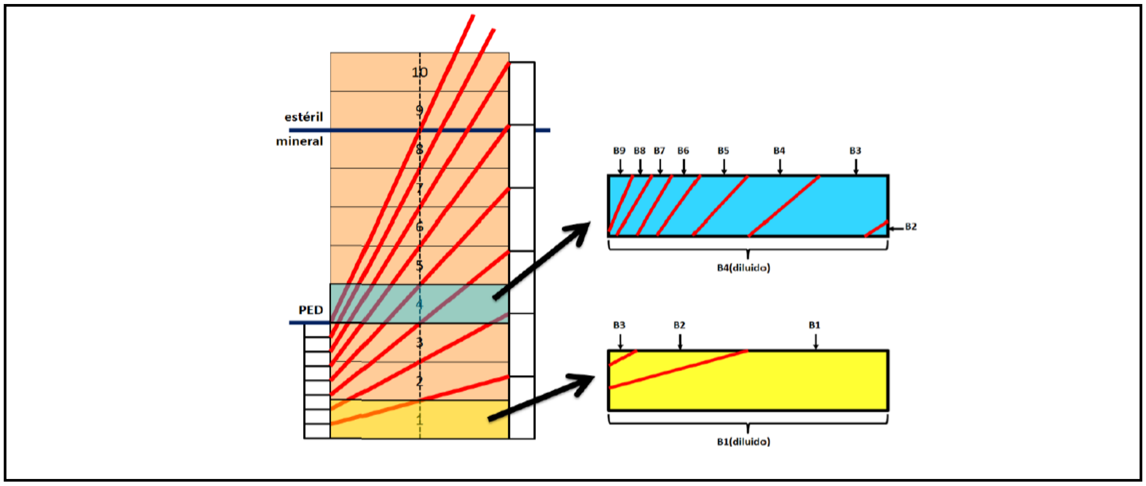

Figure 6: Column's mixing by PDE

From Figure 6 it may also be noticed that the PDE is actually a linear representation of the mixing process. This observation agrees with its mathematical definition:

$$PDE = \frac{H_c - HIZ/(dcf * s)}{H_c} \quad (3)$$

Where,

H_c = Column height (m)

HIZ = Height of Interaction (m)

dcf = Draw control factor

s = Swelling factor

The column height is variable and can be adapted to obtain the desired PDE. There are several Laubscher abacuses available to determine the draw control factor and value of the interaction height, which represents the height where the column starts flowing vertically (Figure 7). The swelling factor is a geotechnical input, and will depend on the rock quality.

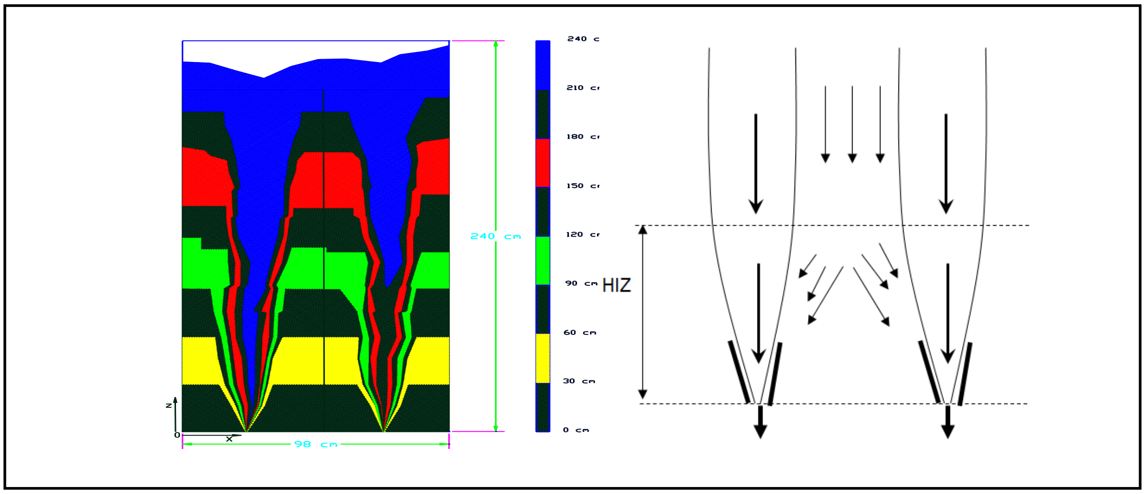

Figure 7: L – rock flow simulation. R – HIZ definition and simplified rock flow direction

It may be inferred from equation (3) that this model works with each column independently, without taking into account the effect of the neighbor columns' reaction to caving. Correspondingly, as the model's output is a linear mixture along the column, and as Figure 6 shows, the diagonal line that represents the waste material entering crosses the column's center at exactly the mid distance of the diagonal, assuming a PDE of 0% would mean that a fourth of the column is replaced by waste, what translates into a dilution of 25%. Now, with a PDE of 100%, there is no waste in the columns, which of course corresponds to a dilution of 0%. Extrapolating these two relations, the PDE value may expressed in terms of dilution percentage value with the following equation:

$$Dilution\ (\%) = 0.25 \cdot (1 - \mathrm{PDE}) \quad (4)$$

According to the studies made by Codelco, the value for the PDE is 50% for the first level and 40% for the following three levels, what translates into a dilution of 12.5% for the first level, and 15% for the subsequent levels (Eq. 4).

4.5.2. Dilution Variability

The Laubscher model is deterministic, i.e. it assumes that ore geometry and mechanical behavior is constant for the block, which is an oversimplification. Here, the in-situ and the diluted block models produced by the Laubscher's method are used to develop a stochastic function, which represents the uncertainty of dilution.

Even though the 40% PDE value considered for the base case translates into a 12.5% dilution, this value is not constant for the whole mine, not even for a particular column. As Figure 8 shows, an ideal case with no dilution presents a constant ore grade until the column has been completely extracted (represented in blue), however, because of dilution, in reality ore grade starts to reduce gradually long before the column is completely mined (in this case study, when the column extraction is approximately 40%).

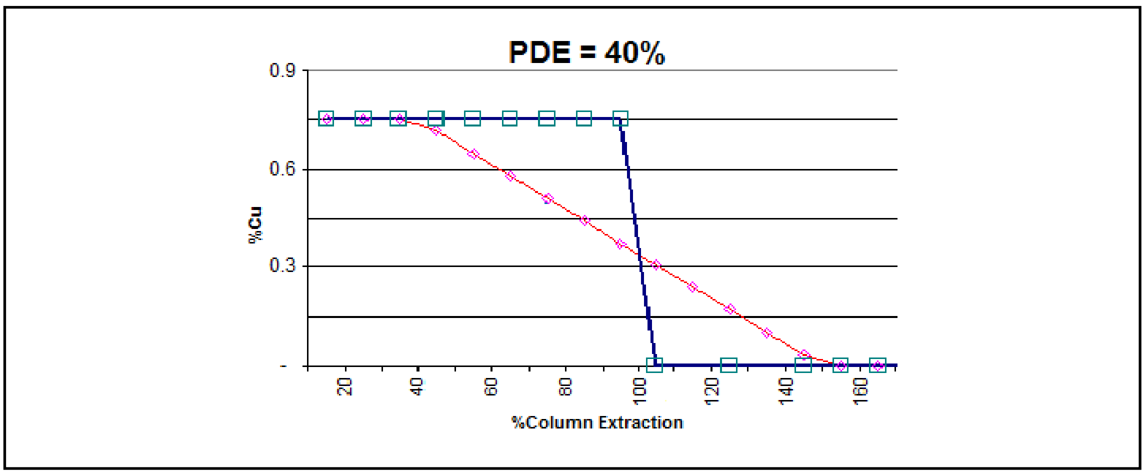

Figure 8: Effect of the PDE along the extracted column

This gradual grade reduction is the source of uncertainty for this particular mixing method, because on one hand, it is impossible to know with anticipation the exact percentage of column extracted when waste material first appears. On the other hand, in reality, dilution doesn't occur linearly as this model supposes, making it impossible to state a certain PDE value, as the mixing may be misleading.

This same effect is presented in Figure 9, where the left image presents the contour of in-situ ore body with the host rock, and the right image shows the resulting ore body after a mixture of a 40% PDE. Three conclusions may be inferred from this image: first, that clearly there is a dilution variability acting upon each column, which may be perceived as a source of uncertainty and risk. Second that Laubscher's volumetric model acts only vertically over the column, without considering the sloping or horizontal flow of waste; and finally, that a probability distribution model for dilution behavior should present a higher frequency for low percentage dilutions (presented in orange on Figure 9), and a gradually reducing frequency for higher values.

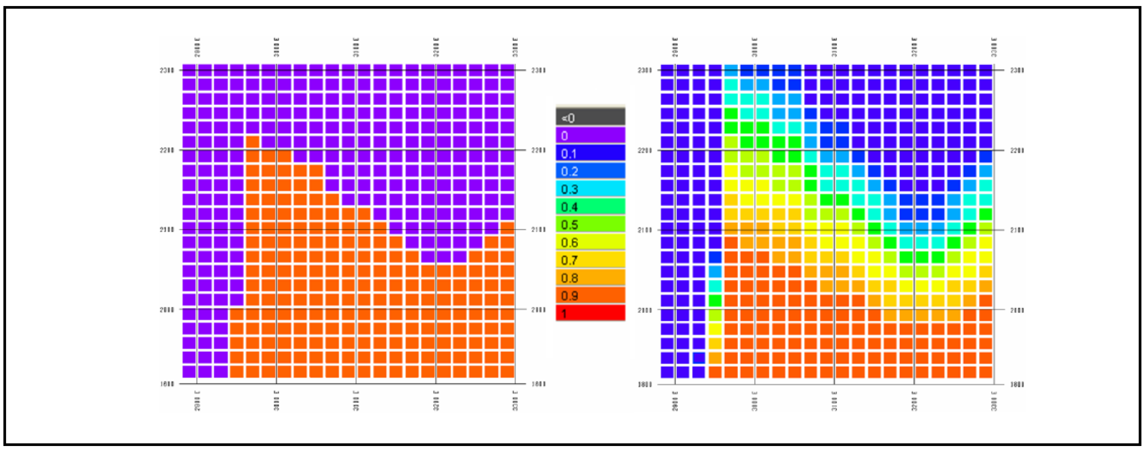

Figure 9: Orebody Contour before (left) and after (right) mixing for a 40% PDE

The gradualism of grade behavior may be expressed as a distribution function, which is obtained by dividing the block model data bases by level, to create 4 sub-databases. Then for each block model (diluted and undiluted, by level), a histogram is created, discretized to the 0.1% copper grade, with its corresponding cumulative probability graphs. Finally, the percentile variability is obtained by comparing by range, the grades of the original in-situ model (left of Figure 9), with the diluted model obtained by Laubscher's simulation (right of Figure 9), as expressed on equation 5.

$$Variability = \frac{\%i_{insitu} - \%i_{mixed}}{\%i_{insitu}}, \qquad \%i_{insitu} > 0 \tag{5}$$

A new histogram is created with the data obtained from the four panels' sub-databases, to obtain the probability of occurrence of dilution value per block.

This procedure allows not only determining the most probable dilution value (base case), but at the same time it models the uncertainty on the variable. The resulting histogram is presented in Figure 10, where the intervals used coincide with the ranges used to obtain the previous variability.

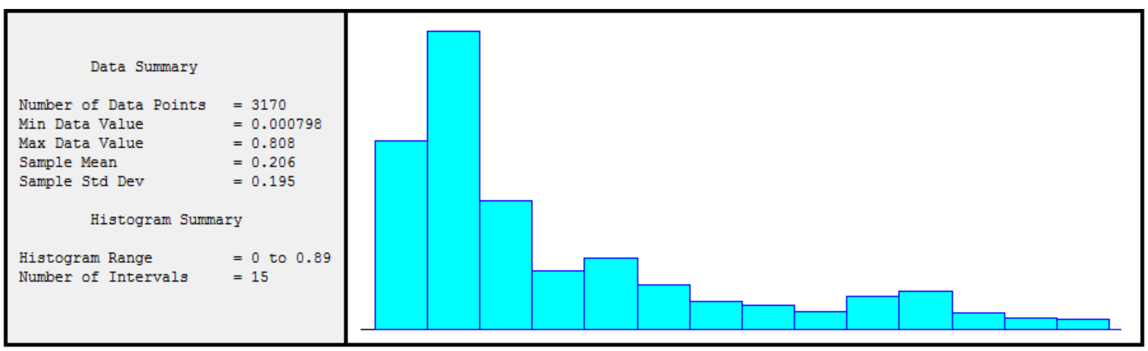

Figure 10: Vertical Dilution's resultant histogram

Loading the values of this histogram into the Student Edition of Arena Software[1], and running the input analysis tool, it is possible to find the probabilistic function that best fits the variable's behavior. With the corresponding parameters obtained by the probabilistic function (mean, mode, standard deviation, etc.) it is also possible to estimate with an order of confidence the future values that can be obtained for this variable.

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[1] This Software specializes in simulation and automation, developed by Systems Modeling, which uses SIMAN processor and simulation language. The Student edition is a free version used for academic purposes.

In this case, the data was best represented by a lognormal distribution, with a mean of 23.1% dilution and a standard deviation of 35.5% (Figure 11). This fit presented a square error of 1.071%, what makes it a very good fit, and a robust method to define the expected value of the mine's dilution. It may also be noticed that, just as it was expected from the observations of Figure 9, low dilution values present a higher frequency, which reduces gradually.

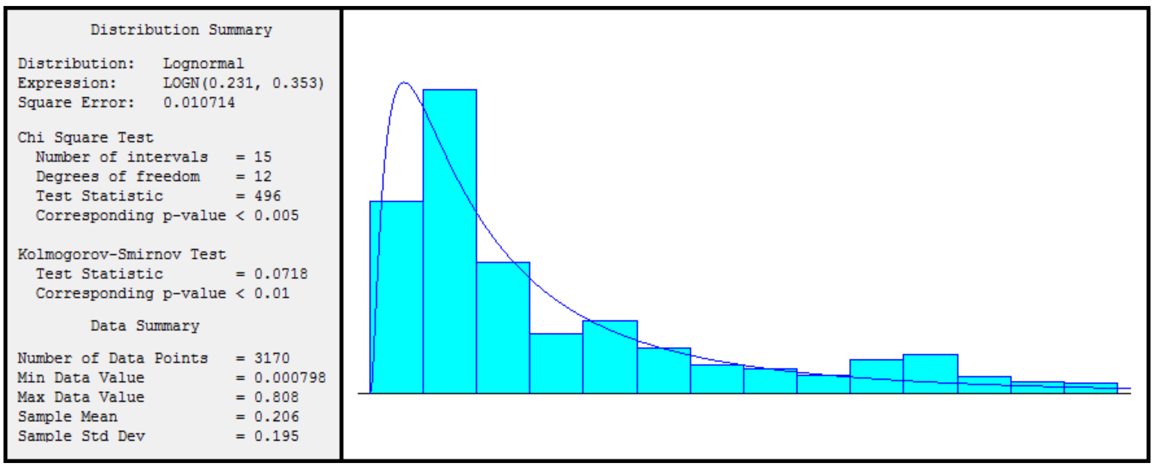

Figure 11: Vertical Dilution's best-fit probability distribution

4.5.3. Horizontal Dilution

A limitation of the model in Figure 9, is that it does not account for the lateral flow into the column from adjacent columns and, more importantly, waste from the host rock at the boundaries of the orebody. Due to the geometry of the Chuquicamata orebody, which presents a great amount of surface area which is directly exposed to dilution, this secondary diluting effect can't be left unattended, as it greatly affect the projects value, by reducing operational recovery, or by reducing ROM grade [58]. This secondary dilution will be denoted as "horizontal dilution", and its calculations are presented in this section. Correspondingly, the current probability function just calculated will be denoted as the "vertical dilution".

As the focus of this study is placed in long term planning (as a yearly basis), the dilution of each single column is not relevant. Therefore, in the estimation of "horizontal dilution" only waste from host rock outside the boundaries of the orebody is considered. In Chuquicamata, the host rock is considered to have a constant grade of 0.1% Cu, 0.002% Mo and 0.003% As.

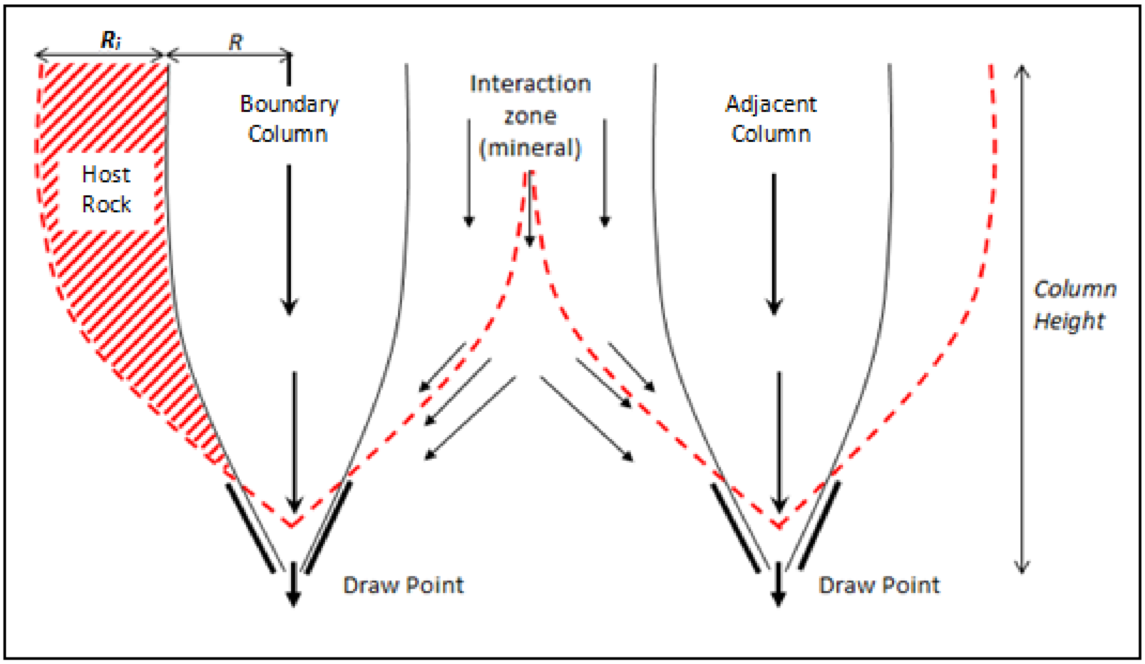

Figure 12: Material interactions by column's extraction

Here, the geometrical model of gravitational flow from host rock waste into columns at the boundaries of the orebody is assumed equal to that of other columns. This model is represented in Figure 12, where "R" is the radius of the gravitational ellipsoid of a given extraction column and "R_i" the radius of influence of a draw point, where w_Z represents the weighting factor, dependent of rock quality by zone "z". Here, horizontal flow into the draw point is represented by the dotted line, where in case of the columns inside the orebody, only ore flows into the draw point and hence, no horizontal dilution is generated. However, at draw points at the boundary of the orebody, horizontal dilution comes from the host rock outside the orebody (traced area in Figure 12). For simplification purposes, as shown in eq. 6, this traced area may be calculated as the area of a right angled triangle, with the length of one side equaled to the column's height (H_C), and the other, equaled to the radius of the extraction column weighted by a rock's quality parameter (R_i).

$$A_\nabla = \frac{H_C \cdot (R_i)}{2} \tag{6}$$

Finally, to calculate the tonnage of waste host rock entering the operation as dilution, the simplified traced area (variable due to rock quality by zone) is multiplied by each level's external perimeter (also discretized by zone) to obtain the total volume of waste material surrounding the deposit (which has the potential to enter the draw-bells), and then multiplied by the house rock's density ($d_w = 2.57\, t/m^3$).

Summing up, the horizontal dilution may be expressed as function of (i) the interaction zone area dependent by zone (eq. 6), (ii) the deposit's perimeter, or length by zone (P_Z), and (iii) waste density (d_w) and total mineral tonnage (t_T).

$$D_H(\%) = f\{\, A_\nabla,\ P_Z,\ d_w,\ t_T\} = \frac{Volume_{DH} \cdot Density_{DH}}{Total\ Tonnage} = \frac{(A_\nabla \cdot P_Z) \cdot d_w}{t_T} \tag{7}$$

Table 3: Zone's Geotechnical and Geometrical data by level

Zone	Level (masl)	Break Angle	Zone Stability	Perimeter (m)	Radius (m)
NE-N	1841	55° - 58°	STABE	1,690	7.56
	1625	56° - 62°		1,500	
	1409	57° - 64°		1,300	
	1193	58° - 67°		1,300	
ES-CS	1841	49° - 55°	MODERATE	1,940	8.21
	1625	51° - 57°		2,000	
	1409	52° - 60°		2,000	
	1193	53° - 62°		2,150	
W-NCS	1841	32° - 35°	UNSTABLE (WEST FAULT)	2,500	12.26
	1625	33° - 39°		2,300	
	1409	34° - 42°		2,400	
	1193	35° - 45°		2,300	

In the geotechnical study by Codelco, the orebody is classified into three zones, according to rock quality, which are shown in the simplified sketch in Figure 13. These zones will be denoted as: the north zone (NE-N); the east and south on the central and southern zone (ES-CS) and the west side on the northern, central and southern zone (W-NCS). The numbers on the interior of each macro-block in Figure 13 correspond to the scheduled year of their extraction, starting in 2019. This shows that there are approximately two macro blocks extracted each year, and that operations on an inferior panel start only once the panel above has been completely extracted.

Knowing the dimensions of each Macro-block, and that the pillars left from north to south have a width of 30 meters, and from east to west a width of 50 meters, each level's perimeter is calculated. Finally, the radius that will be used to calculate the area of the "dilution triangle" is determined taking into account the rock quality by zone. From the data provided by Codelco, each zone is classified by the deposit's geotechnical, geomechanical and geological conditions, to obtain a defined crater height. All this is represented in the value of the subsidence angles (or breaking angle), presented in the third column of Table 3.

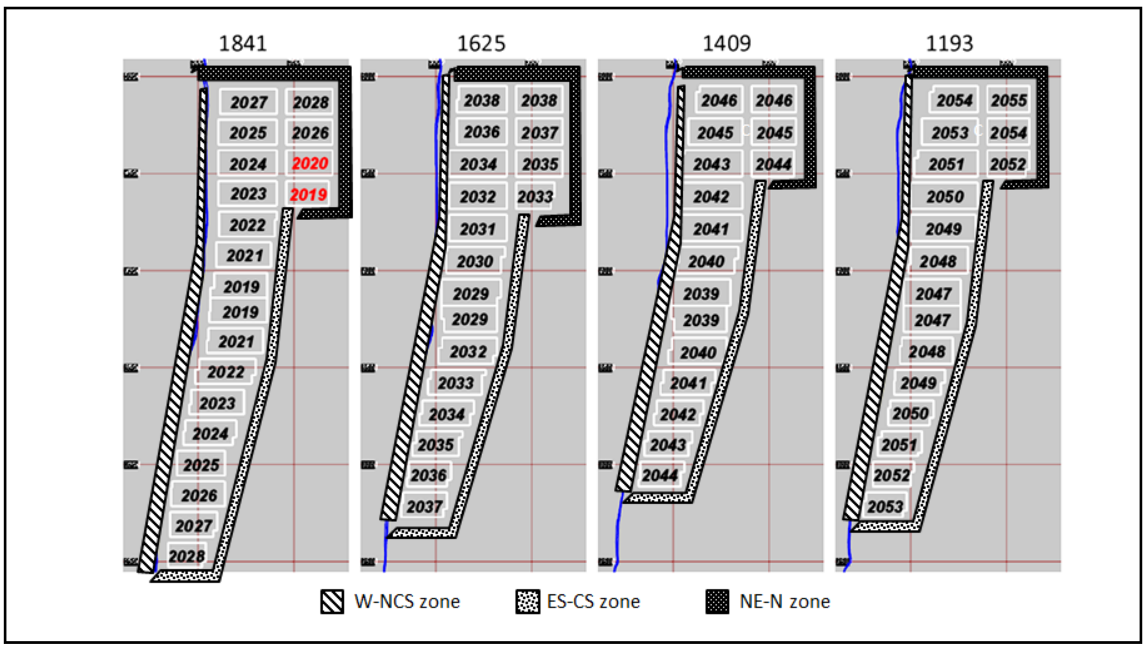

Figure 13: Rock Quality by level's zone

The north zone is considered stable, with an average braking angle of 60°. The central and southern zones in the east side have moderate stability, with an average braking angle of 55° and finally, the west zone is highly unstable due to the west fault that crosses the deposit longitudinally, having an average breaking angle of 37°; even though this angle seems excessively low, the highly unstable characteristics of the west fault that crosses the deposit, and its proximity to the panel, demand to be cautious, and this value was consistently low for the three estimation methods used by Codelco to calculate these breaking angles.

The base case's scheduling was done considering an average subsidence angle of 50° for all the mine, and as the braking angle is inversely proportional to the column's resultant radius, the weighting factor (w_f) for each zone (i) will be calculated as the deviation of each zone's breaking angle value (a_i), from the base case's angle (a_{BC}), as shown in eq. 8 (note that a lower angle means poorer rock quality, causing more rock flow and bigger affected radius).

$$w_{fi} = \frac{(a_i - a_{BC})}{a_{BC}} \tag{8}$$

As presented in the extraction grid in Figure 14, Chuquicamata's mine design's defines a distance between draw points (represented by the blue points of the figure) of about 35m x 16m. This figure represents the extraction details of a macro-block, and according to the deposit's direction, the house rock, or waste material is located to the east or to the west of this particular macro-block. Because of this, the dilution radius is not exactly either one or the draw point's lengths, but rather the oblique distance between the draw point and the east or west end of the ellipsoid created. As defined in Figure 12, by projecting the ellipsoids created by the extraction and the interaction zones, shown in dotted line in Figure 14, the base case radius (R_{BC}) has a length of approximately 9m.

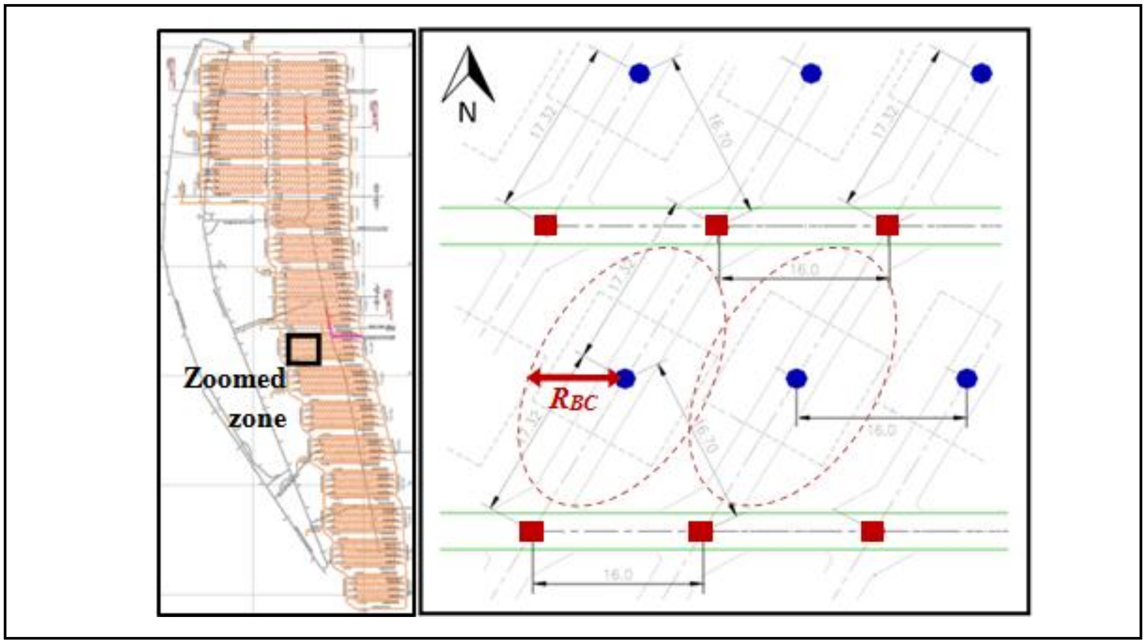

Figure 14: Development drifts with zoomed zone on Draw Point Grid design

With the base case radius as a starting point, the value of each radius by zone is calculated by dividing the base radius (9m) by the weighting factor for each zone, as shown in eq. 9.

$$R_i = \frac{R_{BC}}{(1 + w_{fi})} \tag{9}$$

The obtained results are presented in Table 4.

Table 4: Interaction radius calculation by deposit's zone

Zone	Break-Angle	Rock Quality	Weight factor	Radius (m)
NE-N	59.6°	STABE	0.19	7.55
ES-CS	54.9°	MODERATE	0.10	8.20
W-NCS	36.9°	UNSTABLE	- 0.26	12.20

Finally, to calculate the total horizontal dilution, the total waste tonnage (integrated by zone and level) is divided by the total deposit's mineral tonnage, obtaining a value of

5.064%. In summary, the horizontal dilution (D_H) may be expressed as shown in equation 10:

$$D_H(\%) = \sum_{j=1}^{4}\sum_{i=1}^{3}\left(\frac{P_{ij}(m)\cdot R_i(m)\cdot H_j(m)}{2}\right)\cdot\frac{d_w(t/m^3)}{t_T(t)} = 5.064\% \qquad (10)$$

Where

i = deposit's zone. 1: west side, 2: north-east side and 3: south-east side

j = mine level, from 1 to 4

P_{ij} = Perimeter of zone j on level i (Table 3)

R_i = Average interaction radius of zone i (Table 3)

H_j = Column height of level j (274m, 235m, 237m and 235m respectively)

d_w = Waste rock density (2.57t/m^3)

t_T = Total deposit's design tonnage (undiluted in-situ mineral = 1 435Mt)

As mentioned before, the present case study consists in a long term mine plan, with the amount of detail considered down to the annual production. This means considering a technical variability detailed by zone and by level, not by column. As shown on Figure 13, each and every macro block of the Chuquicamata Mine is in contact with the host rock, and the lengths by zone maintain their proportion between one level and other. Because of this, the horizontal dilution can be added homogeneously to the whole mine plan.

4.5.4. THE DILUTION MODEL

As described before, tonnage dilution has two components: the horizontal dilution, caused by host rock waste material that flows into draw points at the boundaries of the orebody, and the vertical dilution, caused by waste material that flows into the extraction columns from the levels above. The dilution model proposed in the thesis considers that the former acts homogeneously over the deposit, and the latter is represented by the gamma density function shown in Figure 11. The exact relationship is presented in equation 11.

$$D_T = D_V + D_H = f\left(PED_j, H_j, P_j, R_{ij}\right)$$

$$= 0.25 \cdot \left(1 - PDE_j\right) + \sum_{j=1}^{4} \sum_{i=1}^{3} \left(\frac{P_{ij} \cdot R_i \cdot H_j}{2}\right) \cdot \frac{d_w}{t_T} \qquad (11)$$

Adding the constant horizontal dilution to the vertical probability distribution basically moves it to the right, by an exact amount of 5.064%, so the mean, minimum and maximum values increase by this amount, while the standard deviation doesn't change. The global dilution model is presented in Figure 15.

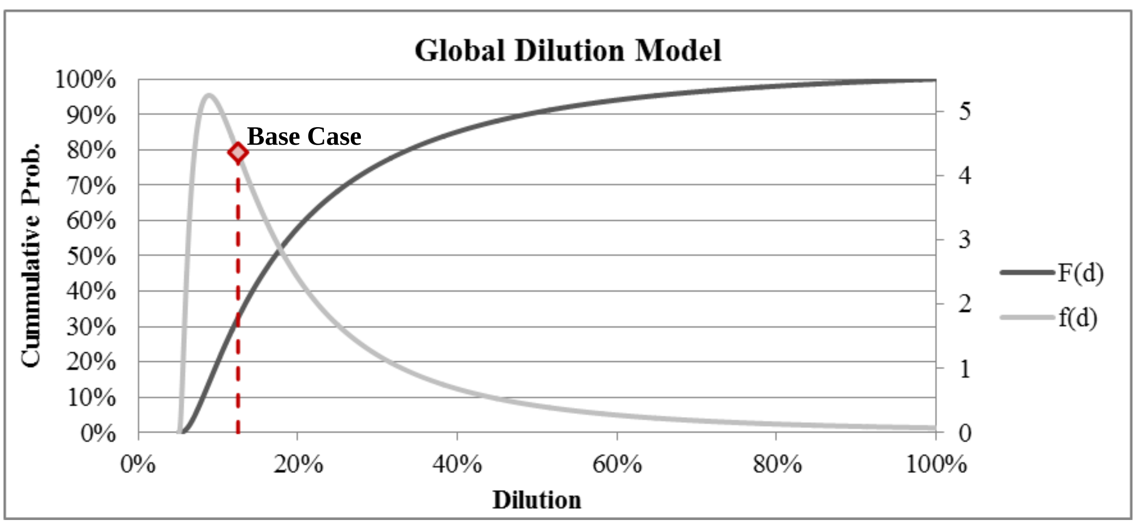

Figure 15: Global Dilution Model

This dilution distribution is an input to our valuation model, as the goal here is to quantify the economic impact (risk) of a high dilution value. Dilution values higher than 12.5% (base case dilution) would increase the amount of waste through the production system and hence, reduce the capacity to mine and treat valuable ore. Consequently, the run of mine (ROM) grade reduces, and copper production fall, as well as the project's value.

4.5.5. *MAXIMUM DILUTION LIMIT*

Even though the dilution's distribution model just developed allows for dilutions of up to 100% (at very low probability of occurrence), this is not a feasible behavior for the mine operation, as the project wouldn't be bankable, and operation would stop before this occurred, or wouldn't start at all. To define the appropriate maximum dilution limit, that represents acceptable "risk free" scenarios for the project, three possible limits are defined:

i. Bankable Dilution (BD)

ii. Project's Maximum Dilution (PD)

iii. Risk-free Distribution Dilution (DD)

Bankable dilution: According to Codelco's Prefeasibility Report, used as the input information for the base case definition, the deposit's reserve is defined by an average ROM copper grade of 0.71%, and a design cut-off grade of 0.4%. This way the "maximum bankable dilution", corresponds to the percentage that dilutes the 0.71% grade ore down to 0.4%. Considering that the diluting rock has a copper grade of 0.1%, the maximum dilution corresponds to:

$$0.71\% \cdot (1 - d_{BD}) + 0.1\% \cdot d_{BD} = 0.4\% \ \rightarrow d_{BD} = 50.8197\%$$

This is the same as considering each column independently, and shutting the draw point once ore grade falls up to a value of 0.4%. With this average dilution, the NPV for the project is MUS$364, MUS$2,214 less than the base case scenario. However, in this case the life of the mine (LOM) extends up to 78 years.

Project's Maximum Dilution: The second dilution definition corresponds to the limit where dilution lowers this independent operation's NPV to zero, what would correspond shutting each draw point when the marginal cut-off grade is met. This limit is found by making a sensitivity analysis to the project's cash flow, to determine how much dilution the project can handle.

$$d_{PD} = 55.8134\%$$

In this case, the LOM is 70 years, and the average ROM copper grade is 0.362%

Risk-free Distribution Dilution: Finally, this limit is obtained by using the parameters of the dilution's probability distribution model, to generate a risk-free scenario with an acceptable level of confidentiality. Figure 16 shows the lognormal distribution model f(d), with its corresponding cumulative probability model F(d). Here, the first maker on the left represents the base case dilution (12.5%), which has only a bit more than a 30% cumulative probability of occurrence (probability of obtaining dilution values of 12.5% or less). By using the distribution's standard deviation, the base case point is stretched out to risk-reduced scenarios represented by the markers to the right on Figure 16. Finally, a risk-free scenario is obtained by adding three standard deviations to the initial dilution value, which is represented by the last marker on the right.

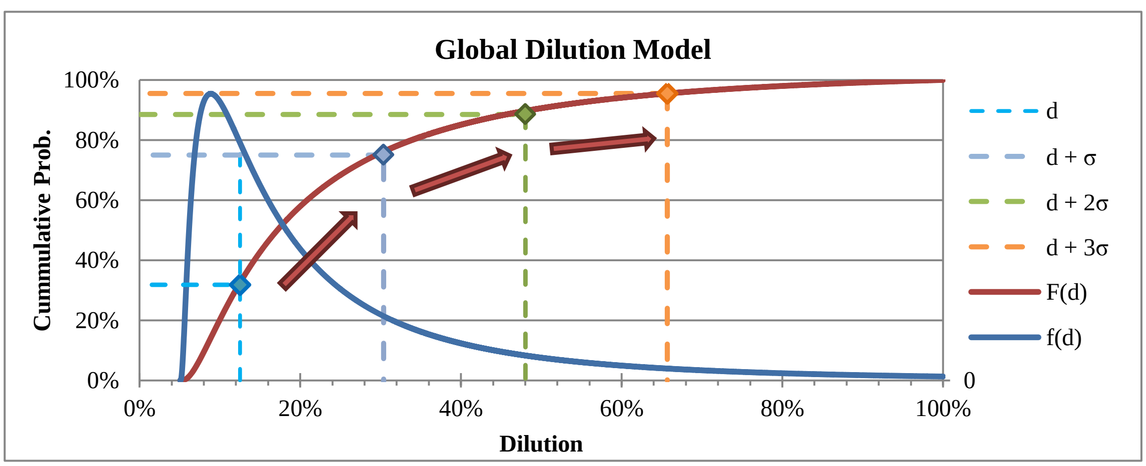

Figure 16: Dilution Model Distribution and Cumulative Probability

These dilution limits are used to quantify the risk reduction, represented by the dilution's cumulative probability. As shown on Figure 16, the distance laps on the 'x' axis are fixed, of a standard deviation, however, on the 'y' axis distances start to shorten exponentially, making it less cost-effective to invest in reducing the dilution's risk.

Because of this slope reduction in the cumulative probability graph, for further calculations, only the limit of two standard deviations will be used to exemplify the risk quantification method by real option valuation, and not the $d + 3 \cdot \sigma$ risk-free limit. In other words, the distribution dilution limit corresponds to:

$$d + 2 \cdot \sigma = d_{DD} = 48.0263\%$$

The exact values of the limits mentioned in Figure 16 are presented in Table 5, together with other range values.

Table 5: Dilution's Probability Distribution Data

Range	Confidentiality	Dilution
1st Quintile	25.00%	10.92%
2nd Quintile	50.00%	17.14%
3rd Quintile	75.00%	29.44%
95% Quintile	95.00%	63.54%
d	33.50%	12.72%
d + σ	76.16%	30.37%
d + 2σ	89.71%	48.03%
d + 3σ	95.50%	65.68%

As Codelco's company structure is quite particular, and the actual dilution values clearly depend more on the probability model (created by technical data), that on the project's costs or net value (governed by financial data and market conditions), for this study the Maximum Dilution Limit will be defined by the distribution dilution: $d_{DD} = d_{DMax} = 48.0263\%$.

4.6. Option's Description & Valuation

4.6.1. Production Rate Simulations

The dilution model (Figure 15) and the expansion costs model (Eq. 2), are used to simulate the performance of the project for varying production rates options above the base case rate of 50.4Mtpa, to determine a rate that reduces dilution's risk to acceptable levels. In this regard, two criteria may be used: i) Hedging NPV and ii) Hedging copper production. These two criteria yield different results, and the decision to choose one over the other depends on management policy.

For both hedging alternatives (i.e. NPV or metal), the "risk acceptance criteria", is defined as the minimum acceptable probability of achieving the "base case performance" (NPV or metal), where the risk acceptance limit may be defined by the multiples of the distribution's standard deviation (σ, 2σ, 3σ, etc). However, a too low risk acceptance criteria may require production rates which in practice, are unattainable for technical reasons (e.g. orebody size and geometry, mining method, etc) and in this case, a perfect risk-free option would not be possible. For the purpose of this case study, a maximum feasible production rate of 75.6 Mtpa has been considered, 50% higher that base case production rate.

The options are obtained by Monte Carlo Simulation, where the project's performance, is calculated for different maximum production capacities. The results obtained for some of the simulations are presented in Figure 17, as the fan-shaped curves, showing the risk of obtaining given NPVs for operations of different capacities (in 10% production increment intervals above the base case 50.4Mtpa). The horizontal curves represent different risk acceptance criteria expressed as multiples of the standard deviation ("$d + s$" and "$d + 2 \cdot s$"), also, the technical restriction of maximum capacity and the base case's expected copper production limit ("Exp. Cu") are included, all in segmented lines. The "Exp. Cu" curve intersects the base case fan-curve ("50.4Mtpa") and the NPV's base case limit in the same point, identified as the Base Case scenario by the circled marker, presenting its risk, ore production and value; and it show that under the initial conditions, there's a 67.5% chance that the project's net present value will actually be lower than estimated. The goal is to lower this risk up to the limit correspondent to the risk-acceptable criteria mentioned before.

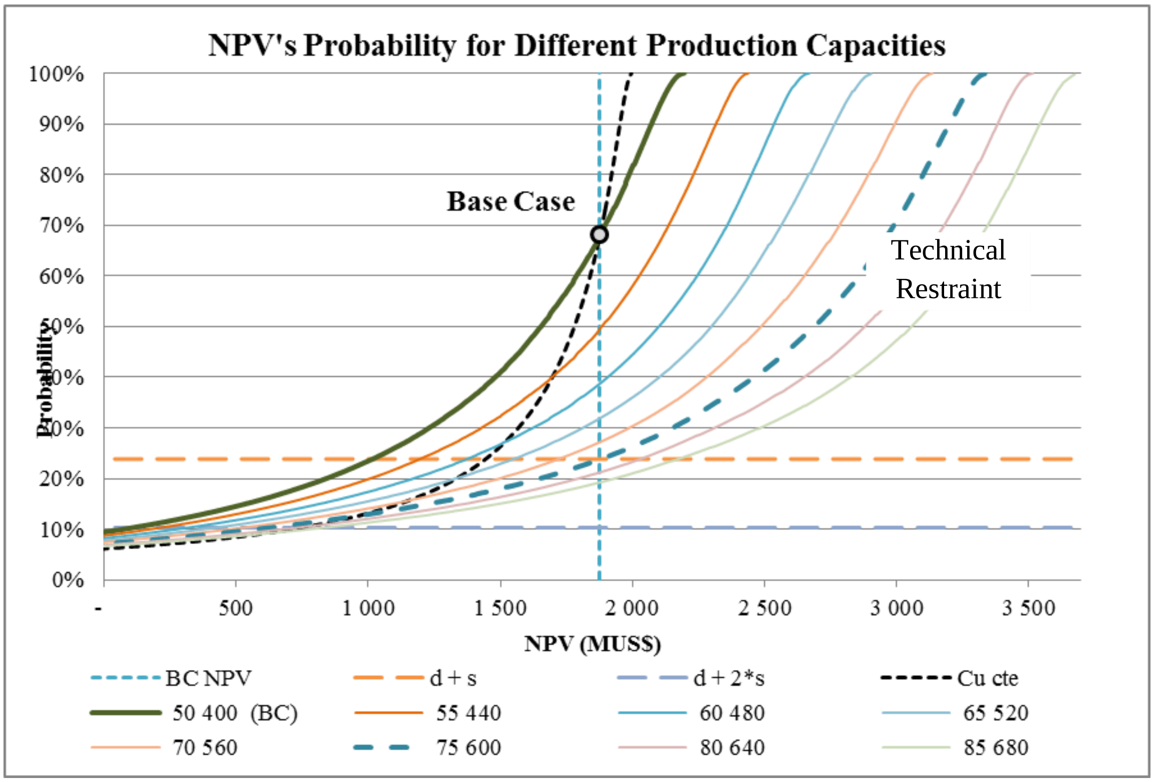

Figure 17: Simulation results for the project's NPV probability for different production rates

These production simulations can be considered as a "catalogue of possible responses" to the dilution's uncertainty in the operation plan, as presented by Cardin et al [9].

From the intersections between the different operations simulated and the expected copper and NPV limits, it is possible to establish a relationship between production and dilution, as shown on Figure 18, in order to obtain the base case's NPV (in light grey) and copper production (in dark grey). In this case, the technical restrain is presented by the horizontal line. Above this line, the options are not feasible. Besides, this figure also shows that the steeper the curve, the less cost effective the options are (as they require higher production increments for the same dilution gaps). By analyzing the slopes of the three segments created by the vertical dilution limits, it is clear that the inclination of the first segment is considerably lower than the rest, which shows that the investment has much better results. Besides from this, it is possible to see that for the $d + 2\sigma$ limit, both options (expected Cu and NPV) require unfeasible measures, and so, only the $d + \sigma$ limit will be considered.

Figure 18 also shows that hedging the project's NPV is more expensive than hedging metal production.

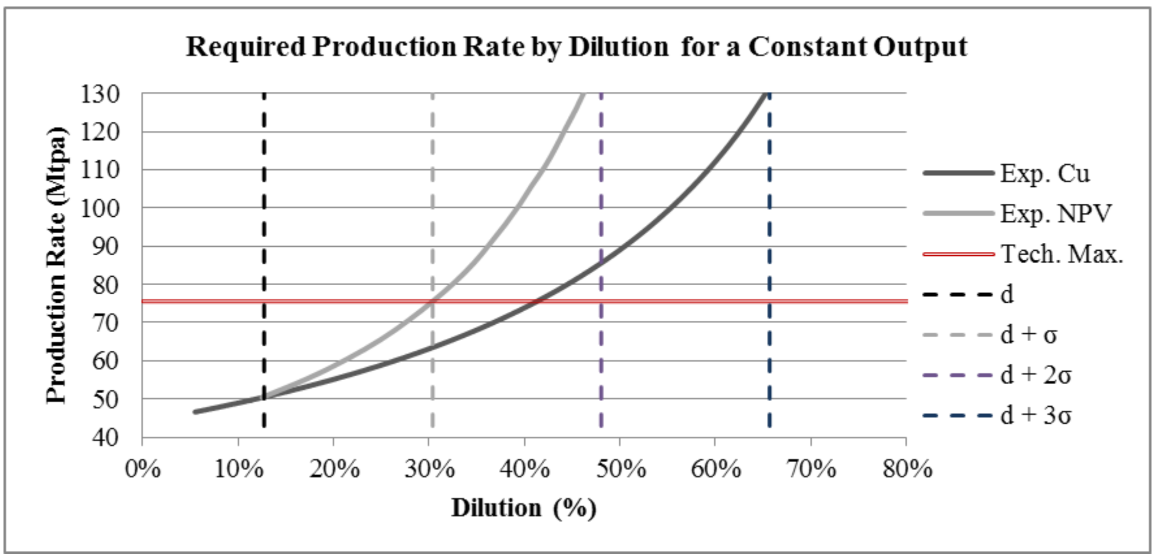

Figure 18: Operation dimensioning that ensures the base case's performance

4.6.2. Option Selection

Figure 19 shows a zoomed image of the zone of interest from Figure 17, where the simulated production rates intersect with the risk-acceptable limit, and the expected copper and NPV limits. It can be noticed (markers in Figure 19) that as it was expected, there are two relevant productivities in this case study, which lower the risk from a 67.5% in the base case, to a 23.84%, at the $d + \sigma$ limit.

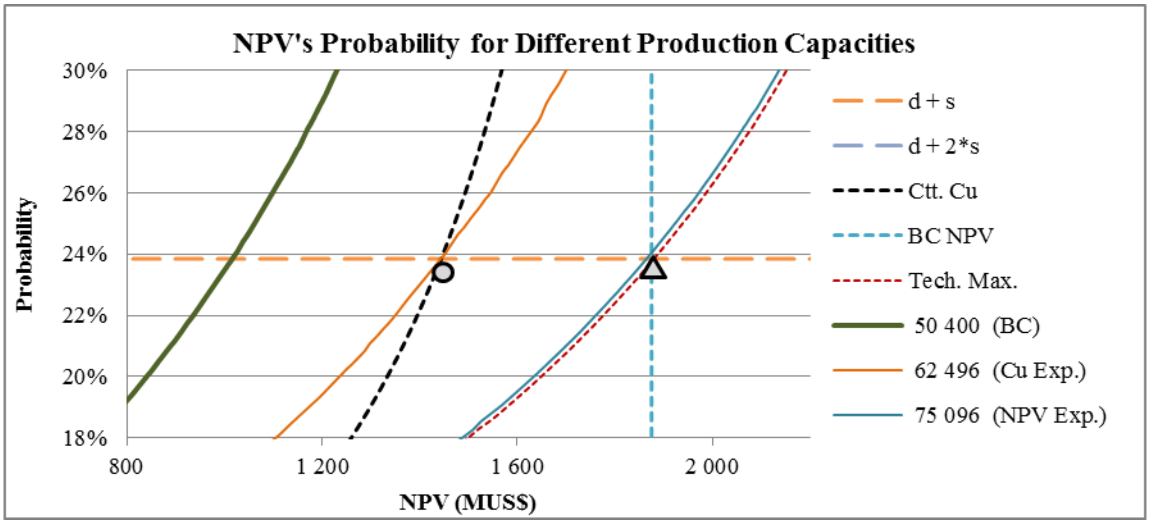

Figure 19: Detail of interest zone from Figure 17

The exact values of these options are presented in the following table:

Table 6: Relevant options' production rates

Limit	***Max. Dilution***	***Risk (%)***	***Expected Cu***		***Expected NPV***	
			(Mtpa)	*%Expan.*	*(Mtpa)*	*% Expan.*
d + s	30.37%	23.84%	62.5	24%	75.1	49%

Even though in this case, these options represent a 24% expansion to obtain the expected copper production and a 49% expansion for the expected NPV, the procedure is exactly the same for any limit or hedging strategy selected.

4.7. Analysis of Results

The simulation scenarios performed above, present a cost structure of a real option with two separate expenses: first, a premium acquisition cost that's paid up front (the project's increased CAPEX), and second, an exercise cost that is paid only if the option is applied. This last expense is accounted for in the variable costs of the OPEX, as it represents the extra costs associated to a larger operation.

4.7.1. Options' Costs

The cost of the option is estimated as the capital expenditures required to provide the project with the extra plant capacity and flexibility it needs to achieve the "acceptable risk scenario". Table 7 shows the project CAPEX and the NPV for the base case and the option for both, NPV and metal hedging criteria. However, the actual cost of the option should be evaluated in terms of differential NPV, taking into account the tax effect of the increased capital expenditures.

Likewise, the NPV value of the option should only include the use of the production capacity required to mill the dilution waste, not considering the possibility of running the plant at rates higher than "base case" rates in terms of "in-situ tpd" (this simulation will be referred to as "limited copper option".

Table 7: Capital expenses and cost by scenario

	Production (Mtpa)	CAPEX PV(MUS$)	CAPEX Cost (MUS$)
Base Case	50.4	$ 1 142	-
Exp. Cu Option	62.5	$ 1 328	$ 186
Exp. NPV Option	75.1	$ 1 510	$ 368

It is worth noting that, as defined above, the cost of the "limited copper option" is a realistic estimation of the cost of the risk associated to ore dilution (e.g. the cost of reducing dilution's risk down to acceptable limits). However, it is not realistic from the operations standpoint, as it is assumed that the upside potential of NPV derived from operating the system at full production capacity is ignored.

Figure 20 shows a graphical representation of the project's NPV for different dilution values, for the three scenarios analyzed: the base case (50.4Mtpa), the expected copper option (62.5Mtpa), and the expected NPV option (75.1Mtpa). This figure also shows the results obtained by the new limited copper options, which correspond to the two inferior curves, under the "Option's Cost" sign. Also, the options' upside potential value for the original scenarios is shown, which will be commented below.

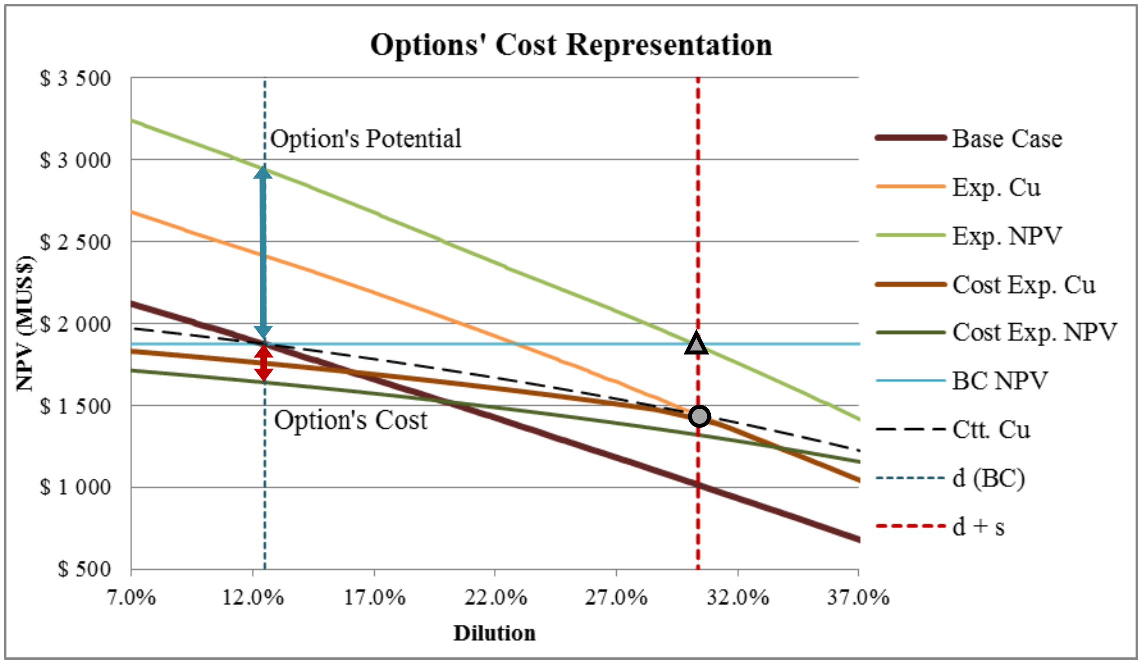

Figure 20: Selected Option's cost and potential value

Note (Figure 20) that the options' cost decreases as dilution increases. This happens because the simulations assume that the base case´s copper production is achieved, and so, the higher the dilution value, the less plant capacity will be left unused.

Option cost and option value for both dilution hedging criteria are summarized in Table 8. The first column in Table 9 shows the maximum annual production capacity for each scenario. The second column shows the base case's NPV, which corresponds to the project's value if the dilution is 12.5% and the mine and plant work at maximum capacity. The column titled "Min NPV" corresponds to NPV if the dilution rises up to its risk-acceptable value, at 30.37% (represented by the circle and triangle markers in Figure 20). The column titled "Constant Cu NPV" refers to the project's value if dilution is 12.5%, and copper production is limited by the base case's production, as explained above. Finally, the column "Option's Cost" is the difference between the base case NPV and the Constant Cu NPV for each option. As it was expected, in this case the options' cost is almost 40% less than the cost obtained by the CAPEX's difference in Table 7.

Table 8: Summary of the options' cost and results

	Production (Mtpa)	BC NPV (MUS$)	Min NPV (MUS$)	Ctt. Cu NPV (MUS$)	Option's Cost (MUS$)
Base Case	50.4	$ 1 875	$ 1 017	$ 1 875	-
Exp. Cu Option	62.5	$ 2 415	$ 1 443	$ 1 756	$ 119
Exp. NPV Option	75.1	$ 2 939	$ 1 865	$ 1 640	$ 235

4.7.2. Options' Upside Potential

The two upper curves in Figure 20 correspond to scenarios where the system is operated at full capacity, this is that the extra capacity available after processing the dilution waste is fully used to process ore at "in-situ tpd" rates above base case rate.

Table 9: Summary of the Options' Potential and Results

	Expansion (%)	BC NPV (MUS$)	Conf of BC NPV	Potential (MUS$)	BC LOM (years)
Base Case	0%	$ 1 875	27.20%	$ -	40
Exp. Cu Option	24%	$ 2 415	64.39%	$ 540	33
Exp. NPV Option	49%	$ 2 939	69.81%	$ 1 064	28

The "upside potential" for each scenario is calculated and shown in Table 9. The first column shows the percent capacity expansion required to meet the project's criteria (NPV or metal). The second column presents the base case's NPV followed by its corresponding level of confidence. The "Potential" column in the fourth column, shows the upside potential of the option, and is calculated as the incremental NPV which may be achieved from using the plant capacity in excess of what is required to process dilution waste. Of course, as Figure 20 shows, dilution increasing causes the option's potential to decrease, as more value must be spent in hedging from the downside risk. Finally, the life of the mine is presented for the three scenarios, considering a 12.5% dilution, and the same 6 years of ramp-up and 5 of ramp-down as in the base case.

4.7.3. Correlated Effects

As shown in the last column of Table 9, there is a very important consequence that must be taken into account by the study: the life of mine (LOM). As the deposit's reserves are limited, if the production rate is increased, the mine's life will decrease. The opposite happens if dilution increases, as there is more material to extract due to the waste that's included. This is presented in Figure 21 where the inverse proportion between the production rate and the life of mine, as well as the directly proportional relation between the dilution value and the life of mine are clearly shown.

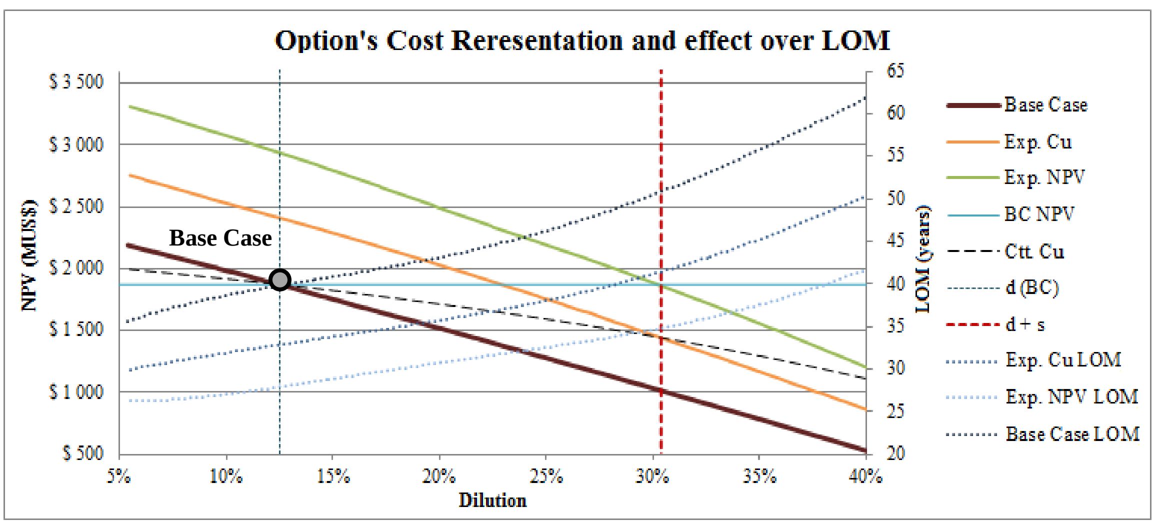

Figure 21: Effects of increased productivities over the mine's life

4.8. Traditional Risk Valuation vs. Real Options Valuation Methods

In order to compare the performance of real-options in quantifying the project's risk, the most common traditional methods will also be used to quantify the risk associated to the dilution's uncertainty. These are: the Expected Monetary Value (EMV) approach, and the Expected Net Present Value (ENPV).

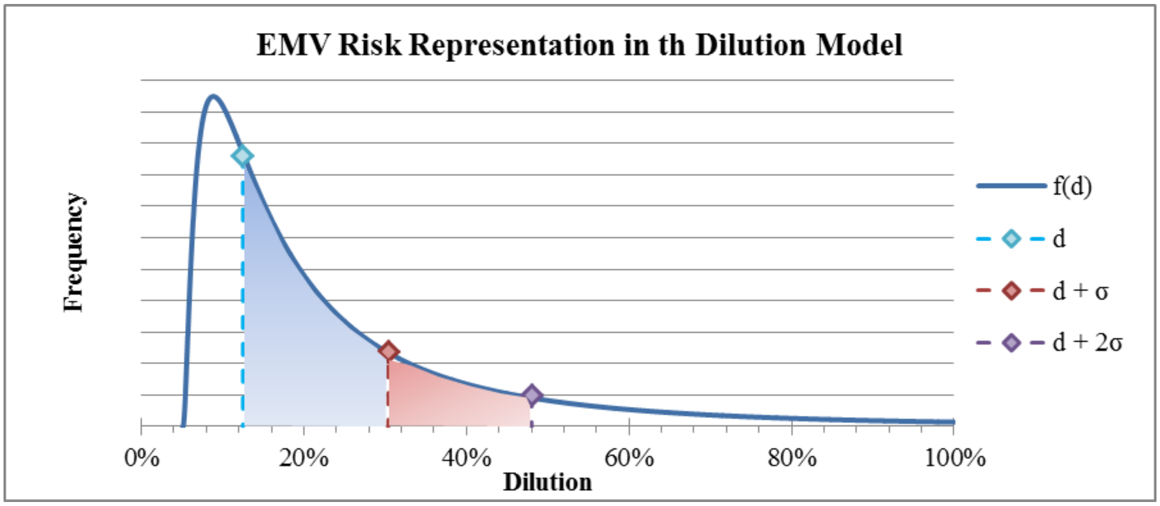

Figure 22: Risk Quantification by Expected Monetary Value

The EMV approach is a scenario analysis, which basically calculates the value difference between the base case, and the worst case scenario, or at least the worst case within an acceptable-risk level. For this case study, the risk-acceptance limit used was the base case value plus one standard deviation of the variable, which corresponds to a 30.37% dilution. The EMV is represented graphically in Figure 22 by the traced areas, and its calculation is shown in equation%, with a final risk value of MUS$ 859 for the 30.37% dilution limit.

$$Risk = \Delta NPV_{EMV1} = NPV_{Base\ Case} - NPV_{d=30\%} = \$1{,}875 - \$1{,}016 = MUS\$\ 859.$$

Clearly, as it was expected, the risk appears to be quite over-estimated compared to the previous methods used, as this procedure is considered to be extremely conservative. This happens because as stated by de Neufville and Scholtes [16]:

"Robustness requires an overdesign of the system, so it functions well under all scenarios (...) this approach commits all capital up front and is thus very costly because only one of the futures may occur."

This can be perceived in Figure 22, as it shows that the variable's uncertainty is treated only as a downside risk, with values higher than the base case, ignoring any possible improvement, or any other value increasing option that could be applied.

Sensitivity analysis may also be used to evaluate the project's performance according to the variable's range of values, but not considering any probability of occurrence of each scenario, only the final impact. Moreover, when using this traditional method, it can be noticed that there is no control or power of decision over the goal of the risk's management, as there was when applying real options by choosing to hedge from the copper shortage or from the NPV loss. A spider graph is created to show the sensitivity analysis for this case study, where the variables included are copper price, molybdenum price and dilution grade (Figure 23).

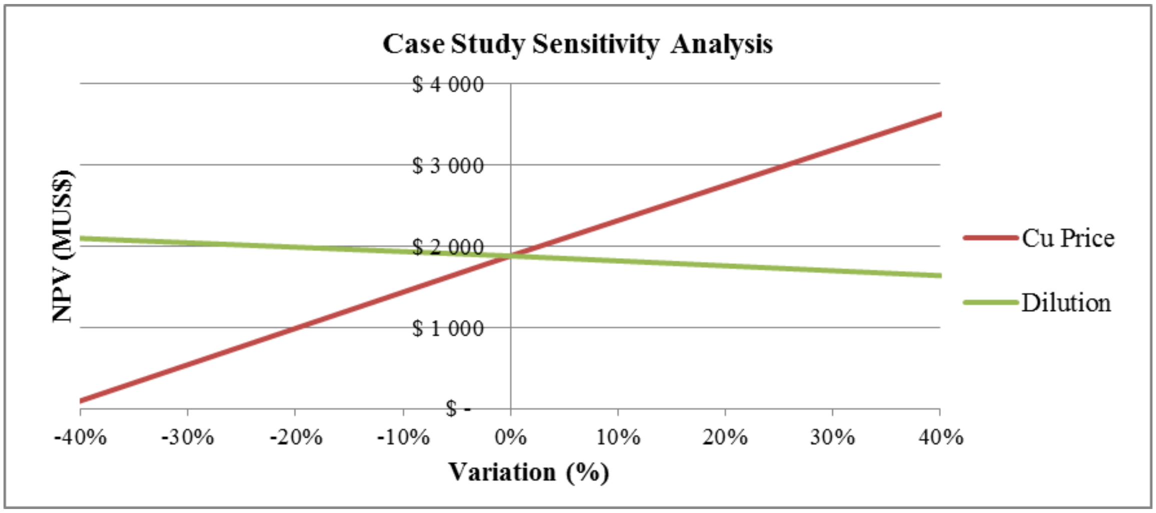

Figure 23: Sensitivity Analysis of the Project's Base Case

It appears that dilution has very little incidence over the project's final value, however, dilution's variability is much higher than price's variability: price variance is often considered to be 20% for base metals, but as it was presented before, dilution can easily increase 300%, leaving this spider graph of 50% with little use. Moreover, dilution has a direct effect over the copper production, and thus, over the effect of copper price over the project, and this correlation is not considered at all in the spider graph. This is why sensitivity analysis, together with the scenario calculations can't be reliable on their own, as they don't consider the variable's actual behavior.

On the other hand, the "Expected Net Present Value" (ENPV), represents the projects' value when taking into account that dilution is uncertain, or in other words, when calculating the project's value as the average of its performance with the dilution as a probability distribution, rather than as a fixed cost. This method is a much more sophisticated, as it recognizes the variable's uncertainty, and thus it allows a better understanding of the project's risk [16], but its main problem is that it fails to recognize and valuate possible opportunities that may arise during the mine life. Finally, as equation& shows, the risk is calculated as the difference between the base case's NPV and the ENPV.

$$ENPV = \frac{\sum_{i=1}^{1000} NPV(D_i)}{1000} = MUS\$1{,}360$$
$$Risk = \Delta NPV_{ENPV} = NPV_{BC} - ENPV = \$1{,}875 - \$1{,}360 = \$515$$

In this case, risk is not as overestimated as with the EMV, however, it is clear that traditional valuation methods use a simplistic view of the project, which delivers conservative values that result in over-dimensioned operations. A quantified risk summary for the defined scenarios is presented in Table 10, showing the results obtained by the capital expenditure difference, by the real options valuation, and by the two traditional quantification methods just described.

Table 10: Risk Quantification Costs for Traditional and Real Options Methods

	Expansion	*CAPEX Cost*	*RO's Risk**	*EMV Risk*	*ENPV Risk*
Base Case	0%	-	-	-	-
Exp. Cu Option	24%	MUS$ 186	MUS$ 119	-	-
Exp. NPV Option	49%	MUS$ 368	MUS$ 235	MUS$ 859	MUS$ 515

The reduced vale of the risk quantified by the real options method* may be explained because, as it was previously described, there are two parts to an option valuation: its cost (acquisition and exercise) and the upside potential of its flexibility.

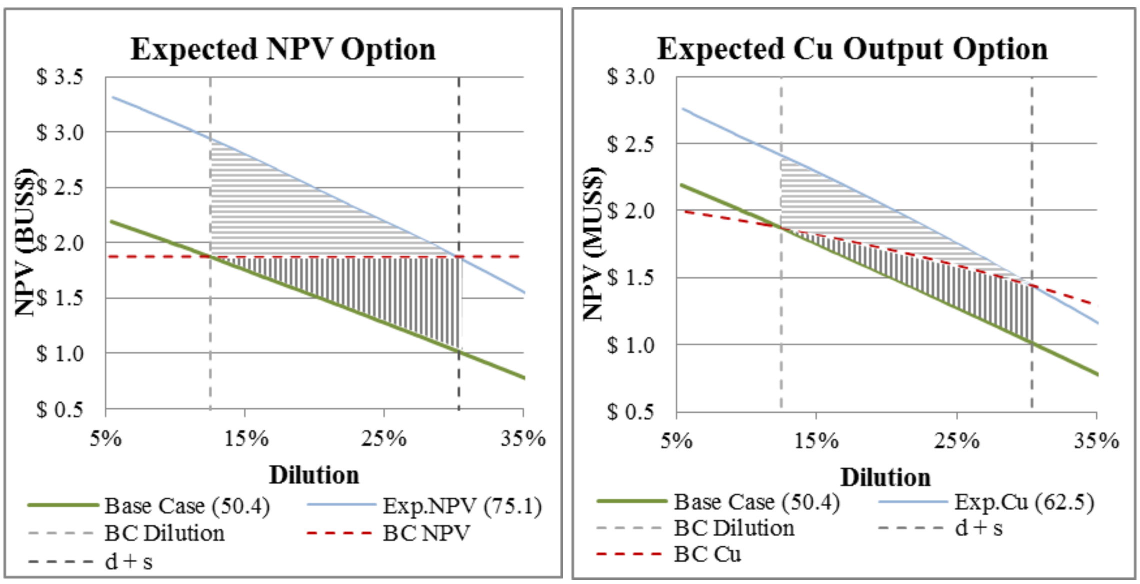

Figure 24: Upside Potential and Downside Risk of the selected options – 1. Cu - 2. NPV

This concept of double consideration is clearly shown in Figure 24, where the upside potential for each scenario is represented by the horizontally traced area, and the hedging cost by the vertically traced area.

4.9. Applicability for Risk Management

In general terms, risk management can be divided into a process of four stages: (1) planning for risk, (2) assessing risk issues, (3) developing risk handling strategies and (4) monitoring risk to see the change over the project. The main advantage of integrating RO into this process is obtained in the effective handling strategies step, in this case, such as Dilution Reduction and Production Rate selection.

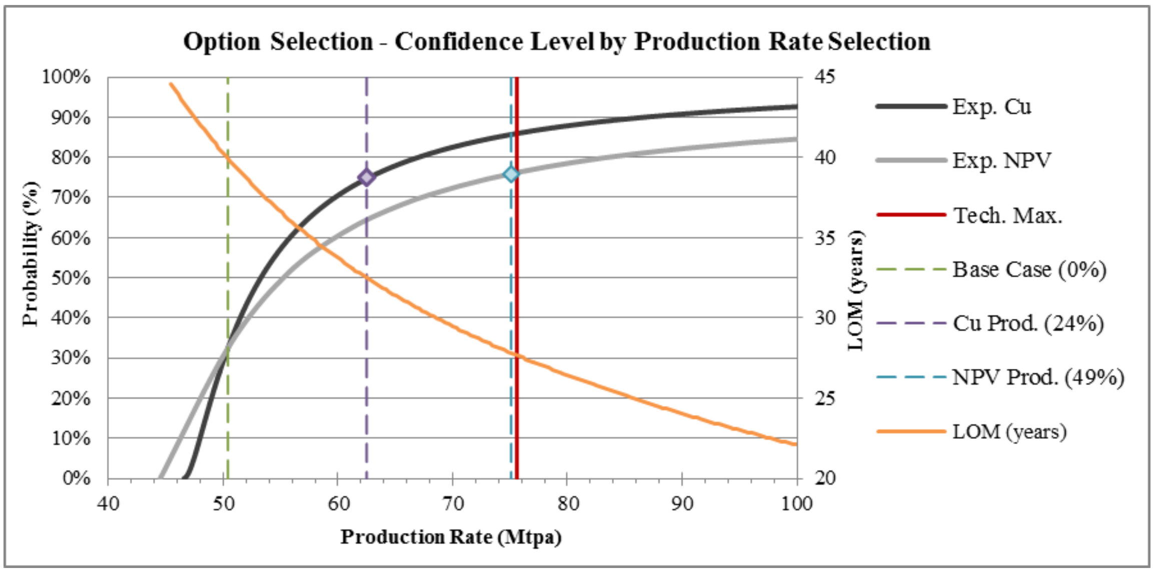

Figure 25: Project's Outcome Confidentiality level according to Production Rates, and their resulting LOM

The main contribution of this study is providing the level of confidence to a given production rate, helping decision makers choose a strategy according to their risk aversion level. With the procedure just presented, it is possible to establish a clear relationship between the production rate and the probability of obtaining an expected project outcome. Figure 25 shows this relation for the present case study, were as the production increases, the level of confidentiality also does, until a technical maximum level of production that delivers roughly a 75% level of confidence for the expected net present value, and approximately an 85% confidence to obtain the expected copper production. These percentages represent the maximum hedging level that is technically feasible for this operation.

It is believed that the research in this thesis represent a significant contribution in the field of application of ROV as a tool to manage risk associated to dilution and other risk parameters intrinsic to mine development projects. Also relevant in this investigation is the contribution to the understanding of the dilution phenomena and its impact on the economic performance of mining projects.

5. CONCLUSIONS & FURTHER STUDIES

As shown in the previous case study, a real options analysis was successfully executed to measure the impact and manage the risk associated to dilution uncertainty in a mining project. Results show that risk quantification by real options reduces in almost four times the traditional method's estimations, providing transparent and reliable results. In conclusion, these options not only quantify the hedging costs, but at the same time, they consider the value they provide to the project, valuating the company's management potential, and thus obtaining a globally optimized operation, rather than a local maximum result that is rarely achievable.

Even though this study focuses solely on the effects of dilution, the same procedure may be applied to other variables without any major variation, such as ore grade, metallurgical recovery and operational performance. These variables are originated on three completely different areas of a mine project; however, the risk they all bring into the project is the same: the possibility of producing less metal than expected. Because of this, the handling strategies and monitoring processes should also be the same. In short, real options can very effectively be applied to manage risk associated to variables that affect the different processes downstream of the system.

Further studies should focus on one hand, on creating risk-clusters that share the same effect over the project's outcome, no matter their origin, and on the other hand, on developing an integrated model which considers these clusters instead of single variables, to finally produce a global risk quantification model that accounts for all risks. Anyhow, a very important measure that must be taken into account when considering integrating various variables in a model is the correlation that exists between them. Maybee [31] presents a comprehensive methodology to account for these effects, which potentially could help with the development of a global risk model.

It's important to mention however, that just as explained in the risk management flow chart presented in Figure 2, not all risks should be handled by the real options method, only the ones that have an effect downstream of the project, like for example the cluster just mentioned: dilution, ore grade, metallurgical recovery and productivity. Together with this, the possibility of short term applications for this methodology should also be revised and studied, as options are available at every level of a mining operation.

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APPENDIX

APPENDIX

A. Production Plan

Year	%	Prod kt	Prod ktpd	Cu %	Cu kt	Mo (%)	Mo (kt)	As (%)	As (kt)	New Area (m^2)	Active Area (m2)	Veloc (t/m2 day)
2018	**2%**	855	2	0.75	6.4	0.05	0.46	0.05	0.4	-	-	
2019	**9%**	4 763	13	0.92	43.9	0.06	2.90	0.04	2.1	101 793	56 166	0.16
2020	**16%**	8 153	22	0.96	77.9	0.06	4.97	0.04	3.4	30 464	118 657	0.16
2021	**38%**	19 381	53	1.07	207.8	0.07	13.92	0.05	10.3	73 744	172 968	0.29
2022	**57%**	28 500	79	1.03	293.0	0.06	18.13	0.05	14.9	75 424	246 369	0.30
2023	**79%**	39 908	110	0.99	394.3	0.06	24.98	0.05	21.0	74 144	308 126	0.34
2024	**90%**	45 232	125	0.98	443.7	0.06	28.90	0.05	24.3	73 040	316 875	0.37
2025	100%	50 400	140	0.94	472.2	0.06	31.55	0.06	28.2	71 088	350 352	0.38
2026	100%	50 400	140	0.87	439.0	0.07	33.11	0.06	30.4	66 496	346 654	0.38
2027	100%	50 400	140	0.85	426.4	0.06	32.00	0.06	31.4	68 192	349 559	0.39
2028	100%	50 400	140	0.82	414.3	0.06	28.73	0.06	29.0	55 232	352 010	0.39
2029	100%	50 400	140	0.78	394.6	0.06	30.49	0.06	30.8	79 810	365 750	0.37
2030	100%	50 400	140	0.79	396.6	0.06	29.89	0.06	29.9	39 690	333 218	0.41
2031	100%	50 400	140	0.82	412.3	0.06	30.04	0.05	25.4	40 800	302 283	0.45
2032	100%	50 400	140	0.82	414.3	0.06	28.63	0.05	24.9	80 360	338 520	0.39
2033	100%	50 400	140	0.75	378.0	0.05	25.65	0.05	23.4	61 640	324 832	0.40
2034	100%	50 400	140	0.70	351.3	0.04	22.53	0.05	22.7	75 070	351 911	0.37
2035	100%	50 400	140	0.67	337.2	0.05	22.73	0.04	21.9	62 760	336 207	0.40
2036	100%	50 400	140	0.62	314.5	0.05	23.39	0.04	22.4	63 280	328 189	0.41
2037	100%	50 400	140	0.61	309.0	0.05	24.39	0.05	23.9	61 960	322 016	0.42
2038	100%	50 400	140	0.59	298.4	0.05	23.13	0.04	22.0	67 280	307 500	0.44
2039	100%	50 400	140	0.64	320.0	0.06	27.97	0.05	26.8	80 610	300 856	0.45
2040	100%	50 400	140	0.62	311.5	0.05	25.45	0.04	19.8	80 980	326 067	0.42
2041	100%	50 400	140	0.68	343.2	0.06	30.74	0.05	23.4	79 140	324 294	0.42
2042	100%	50 400	140	0.71	356.8	0.07	33.57	0.06	29.4	75 950	331 979	0.40
2043	100%	50 400	140	0.64	324.6	0.06	27.72	0.05	26.9	72 760	379 679	0.35
2044	100%	50 400	140	0.61	309.5	0.05	24.80	0.05	27.0	58 220	380 608	0.35
2045	100%	50 400	140	0.60	302.9	0.04	21.12	0.05	23.7	69 360	375 122	0.36
2046	100%	50 400	140	0.56	283.2	0.04	18.65	0.04	20.0	63 280	373 131	0.36
2047	100%	50 400	140	0.58	292.8	0.04	18.95	0.04	18.5	80 240	352 087	0.39
2048	100%	50 400	140	0.60	303.4	0.04	20.41	0.03	17.5	78 200	332 011	0.41
2049	100%	50 400	140	0.70	351.3	0.05	26.61	0.05	23.5	78 670	319 546	0.42
2050	100%	50 400	140	0.71	357.3	0.06	29.94	0.06	27.9	76 520	327 187	0.41
2051	100%	50 400	140	0.66	330.6	0.05	25.45	0.05	26.2	72 560	367 512	0.37
2052	100%	50 400	140	0.64	321.6	0.04	22.43	0.05	26.9	55 240	354 277	0.39
2053	100%	50 400	140	0.62	313.0	0.04	19.96	0.05	27.6	66 910	336 066	0.41
2054	98%	49 499	137	0.59	290.1	0.04	17.42	0.05	24.7	63 280	328 629	0.42
2055	87%	44 095	122	0.59	260.6	0.03	14.60	0.04	19.3	29 920	253 075	0.48
2056	68%	34 087	94	0.58	198.7	0.03	9.71	0.03	10.8	-	162 744	0.58
2057	40%	20 392	56	0.51	104.0	0.02	4.96	0.02	3.1	-	103 383	0.55
2058	8%	3 833	10	0.47	18.1	0.02	0.91	0.00	0.2	-	18 068	0.59
Total		**1.76 Bt**	**0.7**									

B. OPEX

Origin of Expense	Variable	Ud.	Fixed/ Variable	Average (2019-2057)
Gasto Remuneraciones	Extracción	KUS$	v	7 335
	Reducción	KUS$	v	3 299
	Traspaso	KUS$	f	2 216
	Chancado Primario	KUS$	f	3 098
	Ventilación	KUS$	f	-
	Transporte Principal	KUS$	f	1 736
	Transporte Intermedio	KUS$	f	537
	Servicios Mina	KUS$	f	434
	Reparación de Area	KUS$	v	3 027
Gasto Servicios de Terceros	Extracción	KUS$	v	-
	Reducción	KUS$	v	-
	Traspaso	KUS$	v	-
	Chancado Primario	KUS$	f	-
	Ventilación	KUS$	f	-
	Transporte Principal	KUS$	f	-
	Transporte Intermedio	KUS$	f	-
	Servicios Mina	KUS$	f	5 661
	Reparación de Area	KUS$	v	-
Gasto Suministros	Extracción	KUS$	v	-
	Reducción	KUS$	v	11
	Traspaso	KUS$	v	-
	Chancado Primario	KUS$	v	1 249
	Ventilación	KUS$	v	13 095
	Transporte Principal	KUS$	v	23 142
	Transporte Intermedio	KUS$	v	6 165
	Servicios Mina	KUS$	f	72
	Reparación de Area	KUS$	v	65
Gasto Combustible	Extracción	KUS$	v	2 199
	Reducción	KUS$	v	27
	Traspaso	KUS$	v	60
	Chancado Primario	KUS$	v	-
	Ventilación	KUS$	f	-
	Transporte Principal	KUS$	v	-
	Transporte Intermedio	KUS$	v	-
	Servicios Mina	KUS$	f	116
	Reparación de Area	KUS$	v	104
Gasto Materiales	Extracción	KUS$	v	851
	Reducción	KUS$	v	1 419
	Traspaso	KUS$	v	355
	Chancado Primario	KUS$	v	-
	Ventilación	KUS$	f	-
	Transporte Principal	KUS$	v	2 509
	Transporte Intermedio	KUS$	v	2 517
	Servicios Mina	KUS$	f	4
	Reparación de Area	KUS$	v	2 729

Gasto Remuneraciones M&R	Extracción	KUS$	v	3 563
	Reducción	KUS$	v	308
	Traspaso	KUS$	v	414
	Chancado Primario	KUS$	v	1 295
	Ventilación	KUS$	f	-
	Transporte Principal	KUS$	v	977
	Transporte Intermedio	KUS$	v	924
	Servicios Mina	KUS$	f	3 466
	Reparación de Area	KUS$	v	407
Gasto Materiales y Repuestos M&R	Extracción	KUS$	v	4 325
	Reducción	KUS$	v	912
	Traspaso	KUS$	v	383
	Chancado Primario	KUS$	v	3 090
	Ventilación	KUS$	f	3 120
	Transporte Principal	KUS$	v	10 281
	Transporte Intermedio	KUS$	v	3 925
	Servicios Mina	KUS$	v	1 234
	Reparación de Area	KUS$	v	71
Gastos Administración Mina	Administración Mina	KUS$	f	10 058

C. CAPEX

DESCRIPCION		2012	2013	2014	2015	2016	2017
Development for Infrastructure	KUS$	379 112	133 171	78 803	64 092	39 800	33 259
Mine Preparation (2015-2019)	KUS$	0	0	0	10 735	22 372	90 038
Mine Mobile Equipment & Parts	KUS$	0	0	0	0	0	13 317
Total expense for Infrastructure Area	KUS$	0	1 663	1 663	0	257 372	269 736
Engineering and Owner’s Costs	KUS$	101 871	21 191	13 200	13 200	12 730	13 501
Mine Closure Plan MCHS	KUS$	0	0	0	0	0	0
TOTAL INVESTMENT COSTS (KUS$)	**KUS$**	**480 983**	**156 025**	**93 666**	**88 027**	**347 667**	**419 851**
Present Value – SCALABLE COSTS	KUS$	379 112	133 171	78 803	74 827	77 565	136 614
Present Value – NON SCALABLE COSTS	KUS$	101 871	22 854	14 863	13 200	270 102	283 237

2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
28 251	56 298	83 227	54 575	26 123	22 524	5 796	8 095	20 873	63 146	121 459	141 208
19 945	41 111	0	0	0	0	0	0	0	0	0	0
12 855	0	3 200	3 030	7 200	5 923	4 500	7 200	6 773	7 786	3 450	5 975
266 512	15 153	27 302	34 432	38 633	41 105	77 784	92 215	2 253	39 739	4 047	47 898
14 464	10 600	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	179	1 813	1 142	1 765	2 312	2 594	2 775
342 027	**123 162**	**98 336**	**92 037**	**71 956**	**69 731**	**89 893**	**108 652**	**31 664**	**112 983**	**131 550**	**197 856**
61 051	97 409	71 034	57 605	33 323	28 447	10 296	15 295	27 646	70 932	124 909	147 183
280 976	25 753	27 302	34 432	38 633	41 284	79 597	93 357	4 018	42 051	6 641	50 673

2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
38 451	51 187	53 169	37 555	30 999	67 978	82 632	40 620	23 119	38 330	37 503	41 498
0	0	0	0	0	0	0	0	0	0	0	0
5 600	4 800	14 159	3 950	4 000	5 600	5 973	12 320	5 050	4 800	7 700	3 260
30 689	28 717	30 158	28 321	27 676	49 811	50 485	48 533	28 042	29 901	32 687	29 473
0	0	0	0	0	0	0	0	0	0	0	0
4 153	3 228	5 257	2 000	1 439	3 710	2 188	2 323	2 372	2 286	3 651	3 024
78 893	**87 932**	**102 743**	**71 826**	**64 114**	**127 099**	**141 278**	**103 796**	**58 583**	**75 317**	**81 541**	**77 255**
44 051	55 987	67 328	41 505	34 999	73 578	88 605	52 940	28 169	43 130	45 203	44 758
34 842	31 945	35 415	30 321	29 115	53 521	52 673	50 856	30 414	32 187	36 338	32 497

2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053
32 073	54 993	66 466	57 439	20 704	33 163	24 895	16 913	1 790	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
8 800	6 480	2 900	12 607	5 200	9 386	6 723	1 800	7 200	2 400	7 200	3 450
30 283	59 713	61 005	56 521	26 267	27 226	32 279	30 813	28 674	19 898	14 827	7 617
0	0	0	0	0	0	0	0	0	0	0	0
732	2 291	2 069	2 316	2 260	2 686	3 928	2 791	1 109	5 062	2 100	3 467
71 888	**123 477**	**132 440**	**128 883**	**54 431**	**72 461**	**67 825**	**52 317**	**38 773**	**27 360**	**24 127**	**14 534**
40 873	61 473	69 366	70 046	25 904	42 549	31 618	18 713	8 990	2 400	7 200	3 450
31 015	62 004	63 074	58 837	28 527	29 912	36 207	33 604	29 783	24 960	16 927	11 084

2054	2055	2056	2057	2058	2059	2060	Total
0	0	0	0	0	0	0	2 211 288
0	0	0	0	0	0	0	184 201
0	0	0	0	0	0	0	233 153
3 687	0	0	0	0	0	0	2 119 011
0	0	0	0	0	0	0	169 257
2 230	1 465	3 386	2 490	1 970	1 644	358	92 564
5 917	**1 465**	**3 386**	**2 490**	**1 970**	**1 644**	**358**	**5 009 475**
0	0	0	0	0	0	0	
5 917	1 465	3 386	2 490	1 970	1 644	358	

D. NSR CALCULATIONS

COPPER CONCENTRATE

CHUQUICAMATA UNDERGROUND PROJECT

NSR CALCULATION BY TON OF DRY Cu CON.

(Calculations done using Pre-Feasibility Study data– year 2016)

Year		2016
Copper Price	US$/tf	**5 517**
Copper Grade	%	**32.2**
Silver Grade	ppm	**124.0**
Gold Grade	ppm	**0.4**
Humidity	%	**8.5**
Arsenic	%	**1.0**
Metallurgical Discount – Cu	%	**3.4**
TC	US$/tms	**-196.0**
RC	US$/tf	**-330.7**
Silver Price	US$/oz	**14.5**
Gold Price	US$/oz	**950.0**
Silver Met Discount	ppm	**15.0**
Gold Met Discount	ppm	**0.5**
As Discount	%	**0.2**
Penalty...	US$/tms	**-3.0**
...every	%	**0.1**
Sales commission	US$/tms	**-0.6**
Sampling and Analysis	US$/tms	**-0.1**
Total transportation	US$/tmh	**-89.4**
TOTAL NSR US$/T CCs		**1 345.1**
NSR US$/tf		**4 177.4**

MOLYBDENUM CONCENTRATE

CHUQUICAMATA UNDERGROUND PROJECT

NSR CALCULATION BY TON OF DRY Mo CON.

(Calculations done using Pre-Feasibility Study data– year 2016)

Year		2016
Molybdenum Price	US$/tf	**28 200**
Molybdenum Grade	%	**50.0**
Silver Grade	ppm	**0.0**
Gold Grade	ppm	**0.0**
Humidity	%	**8.5**
Arsenic	%	**0.0**
Metallurgical Discount – Mo	US$/tcc	**-380.0**
TC	US$/tms	**-980.0**
RC	US$/tf	**-1380.0**
Silver Price	US$/oz	**0.0**
Gold Price	US$/oz	**0.0**
Silver Met Discount	ppm	**0.0**
Gold Met Discount	ppm	**0.0**
As Discount	%	**0.0**
Penalty...	US$/tms	**0.0**
...every	%	**0.1**
Sales commission	US$/tms	**-4.8**
Sampling and Analysis	US$/tms	**-0.1**
Total transportation	US$/tmh	**-89.4**
TOTAL NSR US$/T CCs		**11 948.1**
NSR US$/tf		**23 896.2**

E. BASE CASE CASH FLOW

(1/4)

		2012	2013	2014	2015	2016	2017	2018	2019	2020
		Lv. 0	Lv. 0	Lv. 0	Lv. 0	Lv. 0	Lv. 0	Lv. 1	Lv. 1	Lv. 1
Production										
In-situ	kt							748	4 167	7 134
Cu	%							0.84%	1.04%	1.08%
Mo	%							0.06%	0.07%	0.07%
Dilution	%							12.5%	12.5%	12.5%
Costs (OPEX)	**$US'000**							**16 811**	**70 614**	**110 656**
Plant Operational Costs	$US/t min							7.88	7.88	7.88
Variable Mining Op. Costs	$US/t min							2.34	5.25	3.71
Fixed Mining Op. Costa	$US							8 076	8 076	16 153
Mill Feed										
ROM Mineral	kt							855	4 763	8 153
ROM Cu Grade	%							0.75%	0.92%	0.96%
ROM Mo Grade	%							0.05%	0.06%	0.06%
Dry Cu Concentrate	kt							17.2	117.7	209.0
Dry Mo Concentrate	kt							0.6	3.8	6.4
Net Sales	**$US'000**							**30 250**	**203 328**	**358 124**
Revenue Befre Tax & Dep.	$US'000	0	0	0	0	0	0	13 440	132 714	247 467
Depreciation Account	$US'000	0	494 906	650 931	744 597	832 624	1 180 291	1 586 703	1 796 016	1 671 710
Yearly Depresiation	$US'000	0	0	0	0	0	0	13 440	132 714	247 467
Revenue before Taxes	$US'000	0	0	0	0	0	0	0	0	0
Taxes (57%)	$US'000	0	0	0	0	0	0	0	0	0
Net Revenue	$US'000	0	0	0	0	0	0	0	0	0
Non Scalable CAPEX	$US'000	105 923	22 854	14 863	13 200	270 102	283 237	280 976	25 753	27 302
Scalable CAPEX	$US'000	388 983	133 171	78 803	74 827	77 565	136 614	61 051	97 409	71 034
Net Cash Flow	**$US'000**	**-$494 906**	**-$156 025**	**-$ 93 666**	**-$ 88 027**	**-$347 667**	**-$419 851**	**-$328 587**	**$ 9 552**	**$149 131**

Base Case Cash Flow (2/4)

2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**
Lv. 1	**Lv. 1**	**Lv. 1**	**Lv. 1**	**Lv. 1**	**Lv. 1**	**Lv. 1**	**Lv. 1**	**Lv. 1**	**Lv. 1**	**Lv. 2**	**Lv. 2**	**Lv. 2**
16 959	24 938	34 911	39 540	44 052	44 059	44 071	44 081	43 947	43 858	43 607	43 254	42 918
1.21%	1.16%	1.12%	1.11%	1.06%	0.98%	0.95%	0.93%	0.88%	0.89%	0.93%	0.94%	0.86%
0.08%	0.07%	0.07%	0.07%	0.07%	0.07%	0.07%	0.06%	0.07%	0.07%	0.07%	0.07%	0.06%
12.5%	12.5%	12.5%	12.6%	12.6%	12.6%	12.6%	12.5%	12.8%	13.0%	13.5%	14.2%	14.8%
217 354	**315 486**	**427 176**	**483 798**	**533 538**	**535 626**	**538 866**	**539 697**	**542 815**	**541 826**	**543 344**	**543 484**	**541 580**
7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88
2.50	2.34	2.22	2.10	2.07	2.11	2.17	2.19	2.25	2.23	2.26	2.26	2.22
16 153	24 229	24 229	32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305
19 381	28 500	39 908	45 232	50 400	50 400	50 400	50 400	50 400	50 400	50 400	50 400	50 400
1.07%	1.03%	0.99%	0.98%	0.94%	0.87%	0.85%	0.82%	0.78%	0.79%	0.82%	0.82%	0.75%
0.07%	0.06%	0.06%	0.06%	0.06%	0.07%	0.06%	0.06%	0.06%	0.06%	0.06%	0.06%	0.05%
557.3	785.9	1 057.9	1 189.4	1 266.7	1 178.4	1 144.1	1 111.2	1 058.2	1 063.9	1 106.0	1 111.6	1 014.6
18.1	23.6	32.4	37.5	40.9	42.9	41.6	37.3	39.6	38.8	39.0	37.2	33.3
965 397	**1 338 645**	**1 810 349**	**2 048 528**	**2 193 140**	**2 098 032**	**2 036 076**	**1 940 286**	**1 895 972**	**1 894 866**	**1 953 623**	**1 939 379**	**1 763 265**
748 044	1 023 159	1 383 173	1 564 730	1 659 602	1 562 406	1 497 210	1 400 589	1 353 156	1 353 040	1 410 279	1 395 895	1 221 685
1 288 840	807 612	247 665	69 731	89 893	108 652	31 664	112 983	131 550	197 856	78 893	87 932	102 743
481 206	573 265	631 903	247 665	69 731	89 893	108 652	31 664	112 983	131 550	197 856	78 893	87 932
266 837	449 894	751 270	1 317 064	1 589 871	1 472 513	1 388 558	1 368 925	1 240 173	1 221 490	1 212 423	1 317 002	1 133 753
152 097	256 439	428 224	750 727	906 226	839 332	791 478	780 287	706 899	696 249	691 081	750 691	646 239
114 740	193 454	323 046	566 338	683 644	633 181	597 080	588 638	533 275	525 241	521 342	566 311	487 514
34 432	38 633	41 284	79 597	93 357	4 018	42 051	6 641	50 673	34 842	31 945	35 415	30 321
57 605	33 323	28 447	10 296	15 295	27 646	70 932	124 909	147 183	44 051	55 987	67 328	41 505
$ 503 909	**$ 694 763**	**$ 885 218**	**$ 724 110**	**$ 644 723**	**$ 691 410**	**$ 592 749**	**$ 488 752**	**$ 448 402**	**$ 577 898**	**$ 631 266**	**$ 542 461**	**$ 503 620**

Base Case Cash Flow (3/4)

2034	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**
Lv. 2	**Lv. 2**	**Lv. 2**	**Lv. 2**	**Lv. 2**	**Lv. 2**	**Lv. 3**	**Lv. 3**	**Lv. 3**	**Lv. 3**	**Lv. 3**	**Lv. 3**	**Lv. 3**
42 840	42 840	42 840	42 840	42 840	42 840	42 840	42 840	42 840	42 840	42 840	42 840	42 840
0.80%	0.77%	0.72%	0.70%	0.68%	0.73%	0.71%	0.78%	0.82%	0.74%	0.70%	0.69%	0.64%
0.05%	0.05%	0.05%	0.06%	0.05%	0.07%	0.06%	0.07%	0.08%	0.06%	0.06%	0.05%	0.04%
15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%
536 392	**536 684**	**537 404**	**543 792**	**547 116**	**550 257**	**552 790**	**547 211**	**547 050**	**546 456**	**549 454**	**557 124**	**560 506**
7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88
2.12	2.13	2.14	2.27	2.33	2.40	2.45	2.34	2.33	2.32	2.38	2.53	2.60
32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305
50 400	50 400	50 400	50 400	50 400	50 400	50 400	50 400	50 400	50 400	50 400	50 400	50 400
0.70%	0.67%	0.62%	0.61%	0.59%	0.64%	0.62%	0.68%	0.71%	0.64%	0.61%	0.60%	0.56%
0.04%	0.05%	0.05%	0.05%	0.05%	0.06%	0.05%	0.06%	0.07%	0.05%	0.05%	0.04%	0.04%
941.1	903.6	843.7	828.7	801.1	859.2	835.1	919.8	957.2	870.8	829.7	813.6	759.3
29.3	29.5	30.3	31.7	30.1	36.4	33.1	39.9	43.6	35.9	32.2	27.4	24.2
1 615 443	**1 567 599**	**1 497 320**	**1 493 478**	**1 436 631**	**1 590 089**	**1 518 275**	**1 713 981**	**1 808 463**	**1 600 641**	**1 500 667**	**1 421 731**	**1 310 701**
1 079 051	1 030 915	959 917	949 687	889 515	1 039 831	965 485	1 166 770	1 261 413	1 054 185	951 213	864 607	750 195
71 826	64 114	127 099	141 278	103 796	58 583	75 317	81 541	77 255	71 888	123 477	132 440	128 883
102 743	71 826	64 114	127 099	141 278	103 796	58 583	75 317	81 541	77 255	71 888	123 477	132 440
976 308	959 089	895 803	822 588	748 237	936 035	906 902	1 091 453	1 179 872	976 930	879 325	741 130	617 755
556 495	546 681	510 607	468 875	426 495	533 540	516 934	622 128	672 527	556 850	501 215	422 444	352 120
419 812	412 408	385 195	353 713	321 742	402 495	389 968	469 325	507 345	420 080	378 110	318 686	265 635
29 115	53 521	52 673	50 856	30 414	32 187	36 338	32 497	31 015	62 004	63 074	58 837	28 527
34 999	73 578	88 605	52 940	28 169	43 130	45 203	44 758	40 873	61 473	69 366	70 046	25 904
$ 458 441	**$ 357 135**	**$ 308 031**	**$ 377 016**	**$ 404 437**	**$ 430 974**	**$ 367 010**	**$ 467 387**	**$ 516 998**	**$ 373 858**	**$ 317 558**	**$ 313 280**	**$ 343 644**

Base Case Cash Flow (4/4)

2047	**2048**	**2049**	**2050**	**2051**	**2052**	**2053**	**2054**	**2055**	**2056**	**2057**	**2058**	**2059**
Lv. 3	**Lv. 4**	**Lv. 4**	**Lv. 4**	**Lv. 4**	**Lv. 4**	**Lv. 4**	**Lv. 4**	**Lv. 4**	**Lv. 4**	**Lv. 4**	**Closure**	**Closure**
42 840	42 840	42 840	42 840	42 840	42 840	42 840	42 074	37 481	28 974	17 333	3 258	
0.67%	0.69%	0.80%	0.82%	0.75%	0.73%	0.71%	0.67%	0.68%	0.67%	0.58%	0.54%	
0.04%	0.05%	0.06%	0.07%	0.06%	0.05%	0.05%	0.04%	0.04%	0.03%	0.03%	0.03%	
15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	
561 205	**563 350**	**557 115**	**558 375**	**555 442**	**553 596**	**551 038**	**518 784**	**436 659**	**329 690**	**210 386**	**55 322**	
7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	
2.61	2.66	2.53	2.56	2.50	2.46	2.41	1.95	1.29	1.08	1.25	2.34	
32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305	32 305	24 229	24 229	16 153	
50 400	50 400	50 400	50 400	50 400	50 400	50 400	49 499	44 095	34 087	20 392	3 833	
0.58%	0.60%	0.70%	0.71%	0.66%	0.64%	0.62%	0.59%	0.59%	0.58%	0.51%	0.47%	
0.04%	0.04%	0.05%	0.06%	0.05%	0.04%	0.04%	0.04%	0.03%	0.03%	0.02%	0.02%	
784.9	814.2	941.7	958.6	886.5	862.8	840.2	778.6	699.1	533.1	279.0	48.4	-
24.6	26.5	34.5	38.8	33.0	29.1	25.9	22.7	19.0	12.6	6.4	1.2	-
1 349 931	**1 411 624**	**1 679 062**	**1 753 497**	**1 587 009**	**1 508 335**	**1 439 599**	**1 317 913**	**1 166 742**	**867 781**	**452 134**	**79 292**	**0**
788 726	848 274	1 121 947	1 195 122	1 031 567	954 739	888 561	799 129	730 083	538 091	241 748	23 970	0
54 431	72 461	67 825	52 317	38 773	27 360	24 127	14 534	5 917	1 465	3 386	2 490	4 460
128 883	54 431	72 461	67 825	52 317	38 773	27 360	24 127	14 534	5 917	1 465	3 386	0
659 843	793 843	1 049 486	1 127 297	979 250	915 966	861 201	775 002	715 549	532 174	240 283	20 584	0
376 110	452 491	598 207	642 559	558 173	522 100	490 885	441 751	407 863	303 339	136 961	11 733	0
283 732	341 353	451 279	484 738	421 078	393 865	370 317	333 251	307 686	228 835	103 322	8 851	0
29 912	36 207	33 604	29 783	24 960	16 927	11 084	5 917	1 465	3 386	2 490	1 970	1 644
42 549	31 618	18 713	8 990	2 400	7 200	3 450	0	0	0	0	0	0
$ 340 154	**$ 327 959**	**$ 471 423**	**$ 513 790**	**$ 446 035**	**$ 408 511**	**$ 383 143**	**$ 351 461**	**$ 320 755**	**$ 231 366**	**$ 102 297**	**$ 10 267**	**-$ 1 644**