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Mine Sequencing Assessment Using Geostatistics and Real Options analysis

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ABSTRACT

The objective of this research was to evaluate a mine sequencing project considering the uncertainties regarding the ore contents and commodity prices through geostatistical simulation and ROA (Real Options Analysis). The methodology proved to be efficient, adding value to the project. The results of the simulation and optimization in the example showed a gain of NPV (net present value) of US $ 0.11 million and a decrease in the variance of the blocks contained in the push backs from 17.95 to 17.85% in the second year of the project. The analysis through Multiple Phased Complex Sequential Compound Option presented a gain of US$ 2.83 million, around 8.20% more than the original NPV. These tools, incorporated in DCF (discount cash flow), proved to be useful.

Keywords: *Net present value; discount rate; Real Options Analysis; volatility.*

INTRODUCTION

Runge (2012) comments that during the last decades, the focus of mining has been on the development of mines in order to take them to production. Demand has outstripped supply and commodity prices reflect this. In this scenery, the winners are the ones who started production earlier, benefiting from non-inflated construction costs and high margins. Now, supply is in balance with demand, and is likely to outperform it.

Competition lowers commodity prices. It is not production alone that matters, but production with efficiency and flexibility. In this globalized world, the well succeed companies are those who understand mining economy and can adapt and change to maintain and improve it.

According to Samis (2001); Dessureault, Kazakidis, and Mayer (2007); Dehghani and Ataee-Pour (2013), mining projects are complex businesses which continuously demand risk evaluation because the value of the project can be altered by numerous variables, whether they are economic (commodity price, operational costs, production schedule, discount rate, inflation, amongothers); geological (grade distribution, density, hardness, etc); orphysicalconstraints (propertylimits, environmental issues, legislation, etc). Thus, the evaluation and estimation of a mining project's value, not to mention the risks of future losses (or opportunities), could certainly lead to unsatisfactory results. Therefore, managers and stakeholders have no other option but to make decisions on in consistent information. According to Abdel Sabour and Dimitrakopoulos (2011), in the practice of a mining project, mine planners cannot know for certain the quantity and quality of the ore in the subsoil. Moreover, the future prices of mineral goods, as well as exchange rates and production costs cannot be precisely known. So, in recent decades, economic and geological uncertainties have been the main target of study. Over the years, many studies have been developed in order to assessun certainties in mining projects. One of the researchers who recognized its importance in mineral projects related to commodity price was Tourinho (1979).As for production costun certainties, one of the earliest publications was Palm (1986);as for geological and grade uncertainties, there are mentions in Dowd (1994) and Dimitr akop oulos and Godoy (2002).Some other authors, such as Drieza et al. (2002) and Shafiee et al. (2009) demonstrate that there are other uncertainties in mining projects. In most cases the initial investment is partially or entirely irreversible which means that acapital investment is required to start the operation, part of which in many cases cannot be recovered. Dogbe et al. (2007), Topal (2008), Akbari et al. (2009) and Evatt et al. (2012) also deal with uncertainties in the classification of mineral reserves. Deutsch (2002) points out that stochastic simulation has been the solution adopted by geostatistics to model the uncertainties associated with the estimate and to reduce risks in the assessment of resources and reserves. These days there are several tools available to evaluate projects both for mining and for any other industrial sector. The most used are: discounted cash flow techniques (DCF) and, in recent decades, Real Options Analysis (ROA).At the beginning of last century (1907), Irving Fisher published the theory of interest and value over time. Although his ideas have been modified and refined, they still form the basis of most corporate investment decisions. However, many professionals claim to be dissatisfied with traditional NPV or other DCF techniques. According to Trigeorgis (1993) and Drieza et al. (2002), it is often evident that such calculations undervalue mining assets. One explanation for this phenomenon is that traditional techniques, appropriate for the valuation of insurance assets, make inappropriate adjustments to account for risk and do not assess the inherent flexibility in managing risk assets. According to Trigeorgis (1993) and Miller and Park (2002), in real market, characterized by changes, uncertainties, and competitive interactions, the implementation of cash flows will probably be different from what management initially expected. As new information comes in and uncertainties about market conditions and future cash flows are gradually resolved, management may have valuable flexibility to change its operating strategy in orderto capitalize on favorable future opportunities or mitigate losses. According to Shafiee et al. (2009), the successful entrepreneur must be able to make decisions to postpone, expand, shrinkorab and on the project at different stages based on ROA. Some strategies can be contemplated in mining investment project to reduce risks and uncertainties in the future such as swaps (risk exchange) and hedges (risk coverage) to explore, develop the project and sell the mineral resources. The main objective of this article is to develop a mixed methodology between traditional and ROA to analyze the feasibility of a project, especially in terms of sequencing push backs in long-term mining planning. To achieve this goal, geological uncertainties in the optimization of push backs sequencing, as well as economic uncertainties in the options leading to managerial flexibility through ROA were considered. A secondary objective was increasing the accuracy of the mine planning in the first years of production.

METHODOLOGY

The first part of the methodology is based on traditional mine planning procedures, the second involves optimization and Real Options Analysis. Long-term mining planning begins with the analysis of drillholes, construction of the geological block model, usually through ordinary kriging to represent the deposit in situ. In the next phase, a Benefit Function (FB = revenues - costs), applied to the geological model is built generating the economic model. Based on this model, the final pit is delineated through an algorithm, in general, Lerchs-Grossmann's (1965). In the subsequent phase, the last pit is divided into large areas called push backs, which form the basis for mine sequencing. Therefore, the NPV of this sequencing was taken as a benchmark. In this methodology, known as traditional, mining planning variables are considered to be known over time, i.e, the block grades, the price of commodities and the cost of production do not change as mining operations take place. In addition, these variables are applied to only one geological block model. And since the production sequence is defined, it does not change, the blocks defined to be mined in a certain period are not reassessed with additional information over time. An example of this methodology is shown in Figure 1.

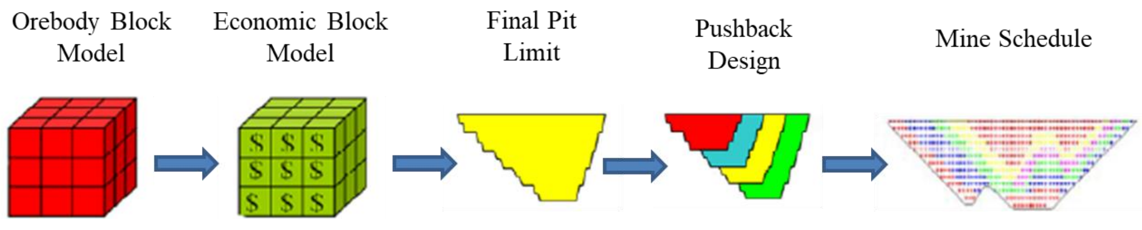

Figure1. *Traditional methodology - adapted from Askari Nasab, H., 2010.*

One of the procedures to incorporate geological uncertainties is the geostatistical simulation of the deposit in such a way that a good representation of the sample space is obtained and the variance of the blocks is reproduced. After the final pit was delineated, the ore blocks contained within it were estimated by means of a Sequential Gausian Geostatistical Simulation. In order to know the whole spatial uncertainty, it was decided to work with 50 probable models. For interpolation, the drillholes were cut by the bounded layer and defined as ore by geology.

After the simulation, the following steps were performed to validate the models: i) Verification of simulation maps; ii) Checking the parameters of the mean and variance of the simulations that should fluctuate around the data of the decluster sample data; iii) Verification of the variograms of the simulated models with sample distribution (histograms). After the geostatistical simulation was validated, the resulting block model was reinserted in the NPV Scheduler. Based on technical considerations of the plant's feed, such as mass and average ore grade, a new mining sequencing was generated.

After the sequencing was outlined, an optimization was made to define the order of the pushbacks mainly taking into account geological uncertainties, but not forgetting grades and stripping ratio (SR). An optimization tool from Real Options' Risk Simulator software was used. Therefore, the NPV of this sequencing was compared with benchmark.

To add managerial flexibility, ROA was used to analyze the sequence of pushbacks. In this assessment, the price of phosphate rock was considered as a stochastic variable; the cost of production was considered as a fixed value estimated from the company’s historical data. The assessment via ROA was made using SLS software from Real Options.

Regarding the stochastic distribution model, the variable price of phosphate rock was modeled by GBM (Geometric Brownian Motion). Volatility was calculated based on a 10-year history of the commodity (July 2009 to July 2020). The data were taken from World Bank reports (https://www.worldbank.org/en/research/commodity-markets) last accessed in July 2020.

In the appreciation of the sequencing project by ROA, the following options were inserted: abandon, contract, expand, and Multiple Phased Complex Sequential Compound Option. First, each option was evaluated separately and secondly, the first three ones, simultaneously in a complete scenario using Complex Sequential Options. In these emulations, if market conditions worsen, the following options can be made: abandon or contract the project. On the other hand, if market conditions improve, pushbacks can be expanded and finally, a neutral scenario using Multiple Phased Complex Sequential Compound Option can be considered.

Due to the complexity of mine planning, a number of variables and algorithms involved, a mixed methodology between traditional and ROA was proposed in this paper. This is shown in Figure 2.

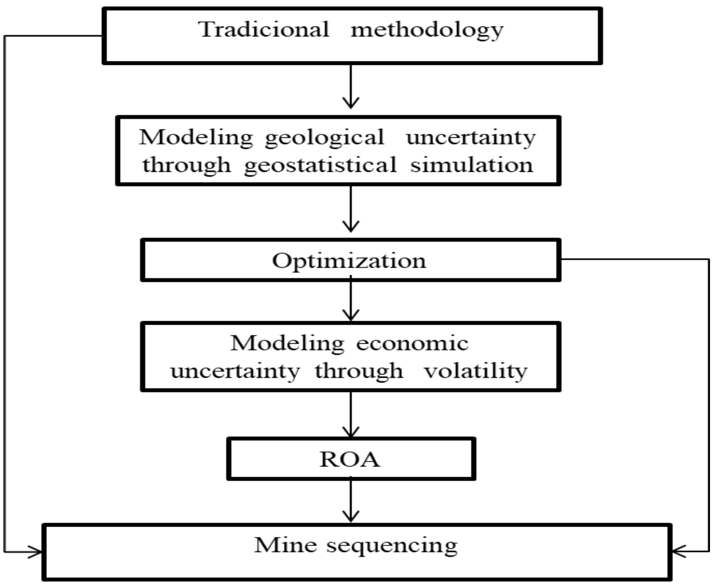

Figure2. *Mixed methodology*

Example of Application of the Methodology

The methodology was applied to a phosphate project located in Triângulo Mineiro, Minas Gerais, Brazil. According to technical reports, the project was envisioned in 2006 and mining operations started in 2010for the exploitation of phosphate ore (P2O5). Thus, some information was passed on by the company in order to prepare this paper.

In principle, during the analysis of the project, mining operations were calculated as being carried out by an outsourced company. That is, the purchase of mining equipment was not contemplated, but the company invested a CAPEX of US$ 35.85 million for the development of the mine up to 1100m elevation and for the beneficiation plant, a CAPEX of US$ 114.28 million. However, the project was designed for a lifetime of 15 years. So, in this methodology, only the first four years of the project were foreseen. The CAPEX of the plant and mine was divided by 15,yearly stablished so as to simplify the analysis of the project. Nevertheless, the value of the CAPEX considered was US$ 40.03 million. As far as geological information is concerned, a database of drillholes containing 9181 samples was analyzed where the probing mesh was more closed at 75 by 75 meters. For the first part of the methodology, a kriging block model provided by the company was used and simplified for two lithologies, one as ore and the other as waste.

By analyzing the block model already cut by the region's topography wireframe, the highest elevation of the probable final pit is around 1270 meters. As for ore blocks, shallower mineralized areas begin to appear at the height of 1100m, whereas the deepest ones, at 960m.

Results And Discussions

Benefitfunction

In order to generate the benefit function, a 5-year history was searched at the world bank from (July 2015 to July 2020) to calculate the average value for the phosphate rock price variable (Figure 3). It is important to note that it has a 10-year history, as this is the period necessary for calculating the volatility, which will be presented below. Thus, the value adopted for the phosphate rock was US $ 94.13/t. For production costs, the company's historical data was used.

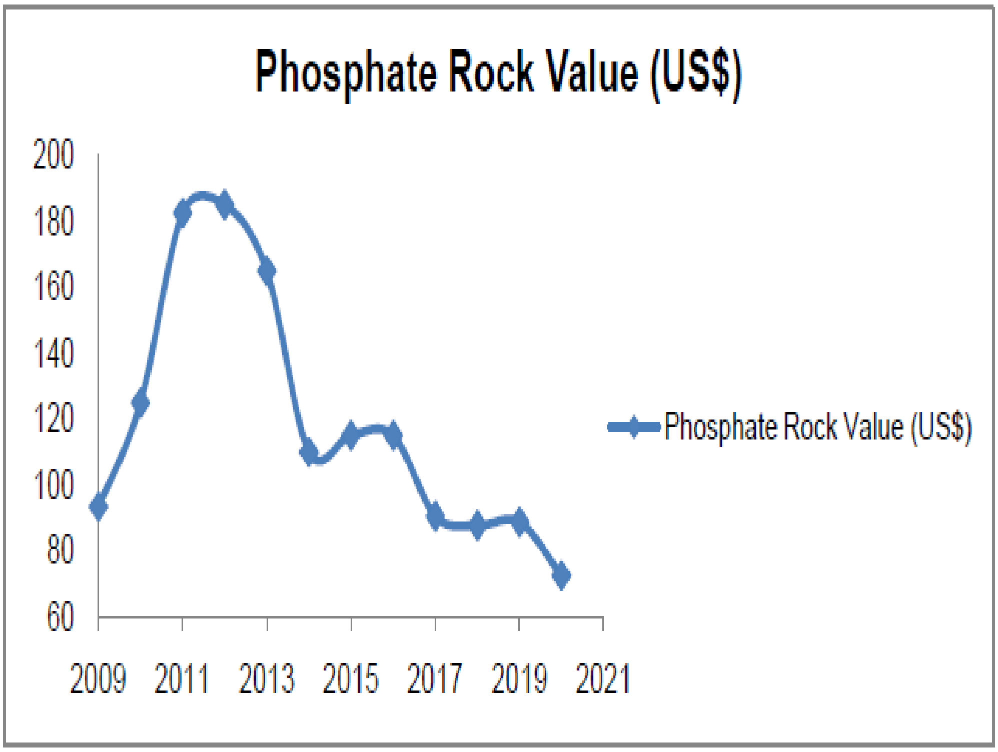

Figure 3. *Price variation in US$/t of phosphate rock for the last ten years*

After the final pit was outlined, pre-stripping of the overburden was performed, and then four independent pushbacks were generated. Figure 4 shows the distribution of the pushbacks as well as the limit of the final pit. Table 1 shows the results of pushback sequencing.

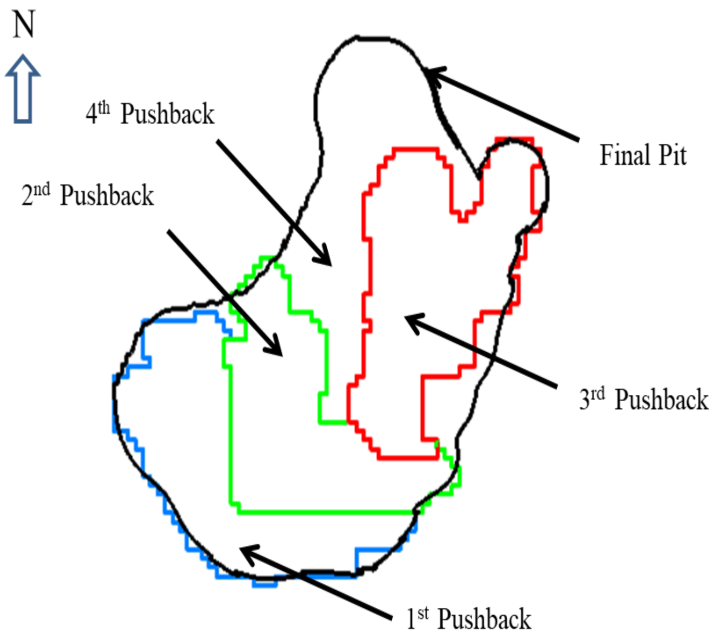

Figure4. *Distribution of push backs and final pit*

Table1. *Pushback data*

SEQUENCING DATA						
Mine sequencing	**Rock**	**Ore**	**Waste**	**Stripping ratio (SR)**	**P_2O_5**	**Risk - Variance**
	tonnes	tonnes	tonnes		%	%
1	21150000	3162500	17987500	5,69	9,7	17,79
2	17937500	4412500	13525000	3,07	12,1	17,95
3	21562500	4162500	17400000	4,18	12,8	17,85
4	42262500	3112500	39150000	12,10	10,4	18,20
Total	**102912500**	**14850000**	**88062500**	**5,93**	**11,25**	**17,90**

The mine was developed to feed a plant with an annual capacity of 3.2 million tons per year with an average content of 11.00% P2O5. Therefore, the calculated yearly revenue comes only from the ore fed at the plant with its respective mass and metallurgical recovery. The rest of the ore mass contained in the pushback refers to the ore released to start the following year, i.e., each calendar year corresponds to a pushback. However, using a discount rate of 15%, suggested by the company, for traditional sequencing, NPV was US$ 34.55 million with an internal rate of return (IRR) of 55%, profitability index (PI) of 1.18, and payback in the second year.

Geostatisticalsimulation

After checking the simulation maps, the histograms were analyzed and it was found that they reproduced the average of the original sample data. Regarding the variance, there was a smoothing. The original variance was 29,65% and the simulated models ranged from 28 to 32%. However, the simulation was done in a more closed grid in relation to the size of the sample data, obeying a limit of points that Sgems managed to simulate, so the grid was 12.5 m x 12.5 m x 5 m. After the simulations, an upscale was made for the original block size.

Figure 5 shows a comparison of the standardized P2O5 variogram (declustering sample data) in red with the simulated data variograms in green. On the x-axis this is the number of lags (distance in meters) used in the variogram and on the y-axis the normalized variance.

As for the initial part of the comparison, the simulated data fit well up to a distance of 100 meters and from this distance on there was a decrease in correlation. Thus, the variogram was better adjusted to shorter distances than the drilling grid, which is consistent with the geological characteristics of the deposit. The variance of the pushbacks ranged from 17.85 to 18.20% (Table 1).

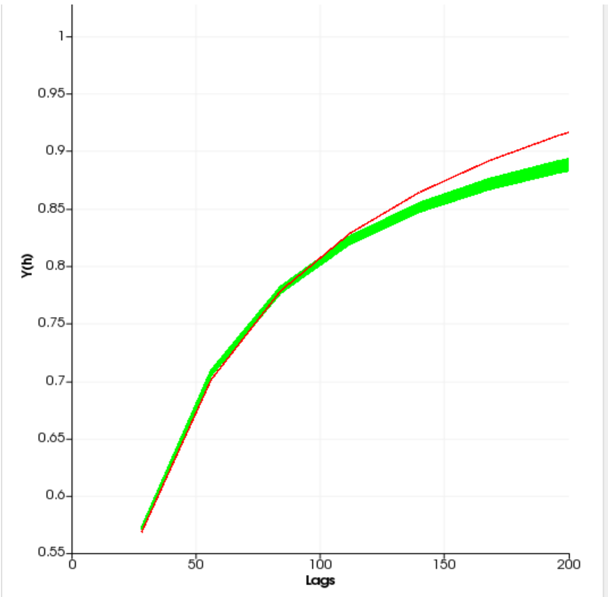

Figure5. *Comparisonofsimulatedvariogramswithnormalizedvariogramofthe original declustering data.*

Optimization

The optimization aimed to reduce the geological uncertainty of the first years of production. For this purpose, the sequence of push backs was placed in increasing order of variance, i.e., the push backs with fewer uncertainties were the first ones to be exploited. This change led to a new NPV for the US$ 34.65 million venture.

Therefore, bringing the push backs with fewer uncertainties to the first years of operation of the mine leads to an increased reliability in the second year of production as the first pushback is the same in both sequences. The order obtained in the optimized sequencing considering the uncertainties for the push backs was: 1st, 3rd, 2nd, and 4th, different from the one initially defined: 1st, 2nd, 3rd, and 4th. The traditional pushback sequence resulted in US$ 34.55 million. So, in this case, there is an NPV gain equal to US$ 0.11 million. This economic gain is due to the higher ore grade of the 3rd pushback compared to the 2nd. It is worth mentioning that normally this optimization prioritizing uncertainty leads to a decrease in NPV.

Real Options

Volatility Estimates

In this example, volatility was measured by using the logarithm of returns on stock values or commodity prices for a 10-year time series (Figure 3). The first step is determining the relative return for a given period, obtaining its natural logarithm (NL), and then calculating the standard deviation of that portion. The result of this calculation is called period volatility. Then it must be annualized by multiplying the value obtained by the square root of the number of periods in the year (e.g.,one, if the data are annual, four if they are quarterly, and 52 if they are weekly). Hence, the volatility value for the period was 12.45%.

Option To Expand

As already mentioned, this case study has four mutually exclusive phases, each one being annual. The Option to Expand was inserted in the project to take advantage of market opportunities for which an investment of US$ 15.24 million is required to expand the company's production by 50%. This option can only be made from the second year onward.

The project has the following input values: NPV without flexibility: US$ 34.65 million, implementation cost: US$ 39.78 million, risk-free yearly rate: 5%, dividend rate was considered zero, and volatility 12.45%.When a binary tree structure is used to calculate the option value, the first step to be performed is expanding the underlying asset in a grid with x-steps. This expansion is built so that the jumps up and down (Randon Walk) are obtained from the volatility of the underlying asset, the size of the step taken by δt and the up and down probabilities.

The calculation formula is shown in Equation 1 and 2. Based on this information, it was possible to expand the binomial tree to 10 steps for didactic purposes (Figure 6). The first cell on the left side is the project NPV without flexibility, and the last cells on the right represent the possible results/paths taken. The binomial tree depends on the number of steps where the greater the number, the greater the precision. Up to 5000-time steps can be used, but generally, with 100 it is possible to have a more accurate result.

$$S_2^{up} = S_1 * UP, \qquad S_2^{down} = S_1 * DOWN \tag{1}$$

$$UP = e^{Volatility*\sqrt{\delta t}} \text{ and } \quad DOWN = 1/UP \tag{2}$$

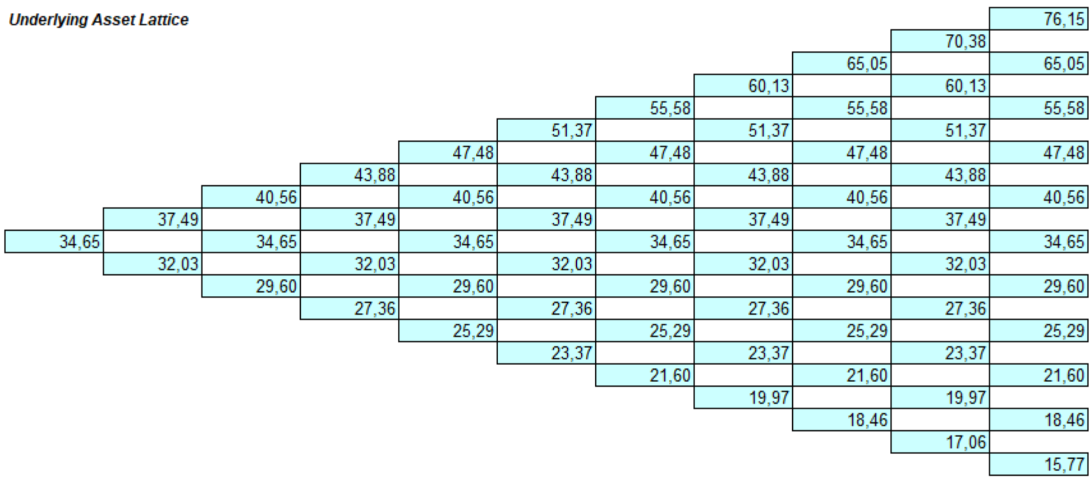

Figure6. *Expansion of the binomial tree for the Expansion Option*

The value of the Expansion Option at time twas calculated by using Equations (3) for the terminal, and (4) for the intermediate Nodes, respectively.

Max(Value_underlying_asset_expanded_time_t; Value_underlying_asset_expanded_time_t * ExpansionFactor - ExpandCost) (3)

Max(Value_underlying_asset_expanded_time_t *ExpansionFactor- ExpandCost; Option Open) (4)The option calculation started at the final node and the maximum value between the binomial underlying asset value or NPV and the net of the underlying expanded asset was verified (Figure 7).

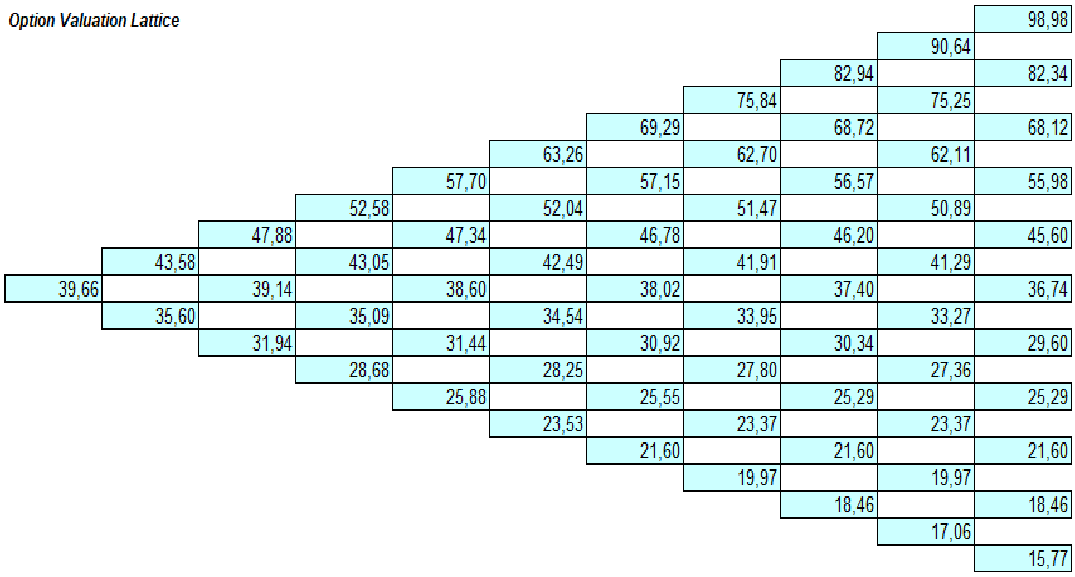

Figure7. *Binomial tree for the Expansion Option*

As demonstrated in Figure 8, the upper part of the binomial tree for the Option to Expand, the decision occurs in the first two upper cells on the right side.

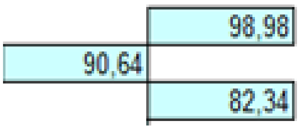

Figure8. *Upper cells of the Option to Expand from the binomial tree*

The calculation to obtain the first upper terminal cell was made according to Equation 3 as follows:

Max((76,15; 76,15*1,5 – 15,24) = Max(76,15; 98,98) = US$ 98,98 million

The bottom cell (82.34) was calculated in the same way. According to Cox et al. (1979), the great mystery of this model is the composition of the Expected Value (90.64) of the tree in Figure 8. The expected value in t is equal to the option's high value multiplied by the high probability (probup) plus the option's down value multiplied by the down probability (probdown). The special or "artificial probability" as it is called, was obtained according to Equation 5 and 6.

$$\text{Probup} = \frac{e^{(\text{Rf} - \text{Dividend})*\delta t} - \text{DOWN}}{\text{UP} - \text{DOWN}} \qquad (5)$$

$$\text{Probdown} = 1/\text{Prob}_{\text{up}} \qquad (6)$$

The Expected Value of S at t was obtained as follows: the expected value of the option in t is equal to the its probability of 60.85% being US$ 98.98 million plus its likelihood of taking the lower position (39.15%) of US$ 82.34 million. The result of the Expected Value of the Option in t is US$ 92.46 million. As these special probabilities are used in the calculation of the Expected Value of the Option, the update of the obtained value, to t-1, was carried out with the risk-free rate Rf, i.e., the expected value was brought one step back as if the option portfolio had no risk but the remuneration of a risk-free investment. Thus, in this case study, Rf = 5% and the discount factor could be calculated by the expression: e(-Rf * δt).

Option (t-1) = Expected_Value * Discount_Factor

Option (t-1) = 92,46 * 0,9802 = 90,64

The value of the option cell at t-1 was obtained, again, by applying the Intermediate Node equation (Equation 4).

New NPV value at t-1 = max (90.64; 70.38) = US$ 90.64 million

For decision-making, one must observe which portion is greater in t-1; if you are on the left, the decision is to expand; if most are on the right, the decision is not to expand. By applying this process to the last cell on the left, the result was NPV value at t = 0equivalent to US$ 39.66 million with 100 steps. The difference is US$ 5.00 million, the value of the Option to Expand,i.e., around 14.4% of NPV without flexibility. It should be emphasized that in this case the results of the calculation reached the same value as both 10 and 100 steps.

Option to Contract

The Option to Contract was inserted in the project to avoid capital losses due to the drop in demand or price of phosphate rock on the market. In this case, the Option to Contract reduced to 30% concerning the original production, and the initial step was from the second year onward. Savings are the costs that can be economized by executing this option. Therefore, in the second year, US$ 13.78 million could be saved; in the third year, the amount was US$ 15.51 million, and in the fourth year, US$ 20.92 million.

The calculation of the Option to Contract was similar to the Option to Expand. The difference in NPV is US $ 0.26 million, that is, the value of the Option to Contract.

Option to Abandon

The Option to Abandon is inserted in the project as a possibility to leave the enterprise and recover the value of the project's asset or intellectual property so as to reduce additional losses. The Option to Abandon can only be executed after the second year when the mine is already in operation. So, the amount "saved", if the option is taken up, just corresponds to the sale of the plant's equipment, about US$ 18.28 million. It is important to point out that the values of the mining equipment were not taken into account as the operation was considered to be outsourced. After the option was executed, the result was the same as the entry's NPV;

therefore, the Abandonment Option does not add value to the project.

Multiple Phased Complex Sequential Compound Option (Mpcsco)

All information individually presented in the Expand, Contract, and Abandon Options was inserted in this one. However, in orderto evaluate the project by using MPCSCO, it is necessary to know the present value of the implementation costs and the maturity of each phase of the project. So, the costs of each phase (1, 2, 3, 4) in millions of dollars were, respectively: US$47.13; US$45.94; US$51.69, and US$69.75.

The binomial tree has 100 steps, i.e., 25 steps for each phase since the duration of the projectis four years. Figure 12 shows the expansion of the binomial tree for MPCSCO.

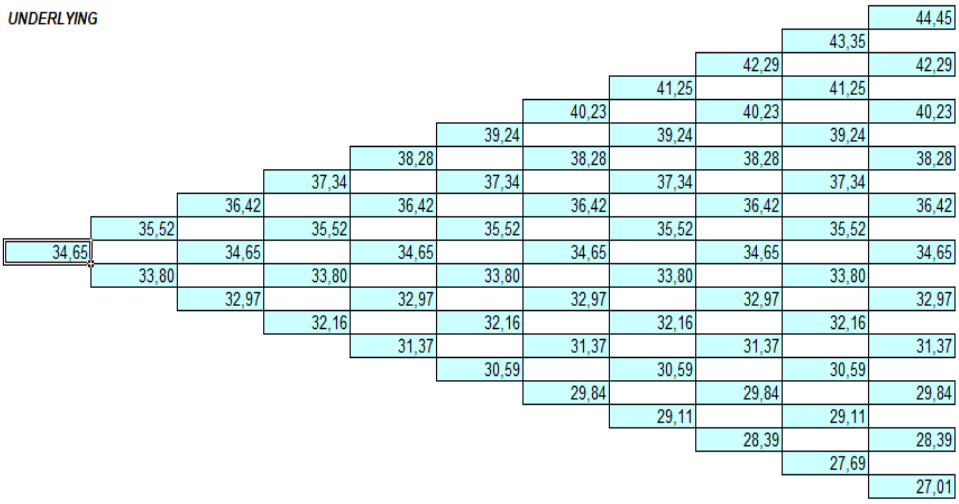

Figure12 . *Expansion of the binomial tree for MPCSCO*

Equations 7 to 10 are used to evaluate the options at each decision node:

Phase1:Max(Phase2-Cost, Phase2 *Contract +Saving, Salvage, Underlying*Expansion-ExpandCost,0) (7)

Phase 2: Max(Phase3-Cost, Phase3* Contract+ Saving, Salvage, Underlying*Expansion-ExpandCos (8)

Phase 3: Max(Phase4-Cost, Phase4* Contract+ Saving, Salvage, Underlying*Expansion-Expand Cost,0 (9)

Phase 4: Max(Underlying-Cost, Salvage, Underlying* Expansion-Expand Cost) (10)For intermediate nodes, Equations 11 to 14.

Phase 1: Max(Phase2-Cost,Phase2* Contract+ Saving ,Salvage, Underlying*Expansion-Expand Cost, Option Open)
(11)

Phase 2: Max(Phase3-Cost,Phase3* Contract+ Saving, Salvage,Underlying*Expansion-Expand Cost, Option Open)
(12)

Phase 3: Max(Phase4-Cost,Phase4* Contract+ Saving, Salvage, Underlying*Expansion Expand Cost, Option Open) (13)

Phase 4: Max(Underlying-Cost, Salvage, Underlying*Expansion-Expand Cost, Option Open) (14)

Therefore, the maximum among the three options was verified, the asset value was multiplied by the contraction factor (0.3) plus the additional gain resulting from the contraction or the asset value multiplied by the expansion factor (1.5) minus the cost of option deployment, or the value of Salvage, opposed to the Option Open value.

The option which obtained the highest value was used in the option cell. As demonstrated in the option trees in Figures 13 – 16,the value of the option is calculated backwards, i.e, from phase 4 towards phase 1.

Thus, the value of the option was only known in phase 1 after subtracting the NPV value without flexibility.

Then, by calculating the value of Option t-1 to the last cell on the left from the 4th to the 1st phase, the value of NPV at t = 0 wasUS$ 37.48 million. The difference was US$ 2.83 million, which corresponds to the value of the MPCSCO.

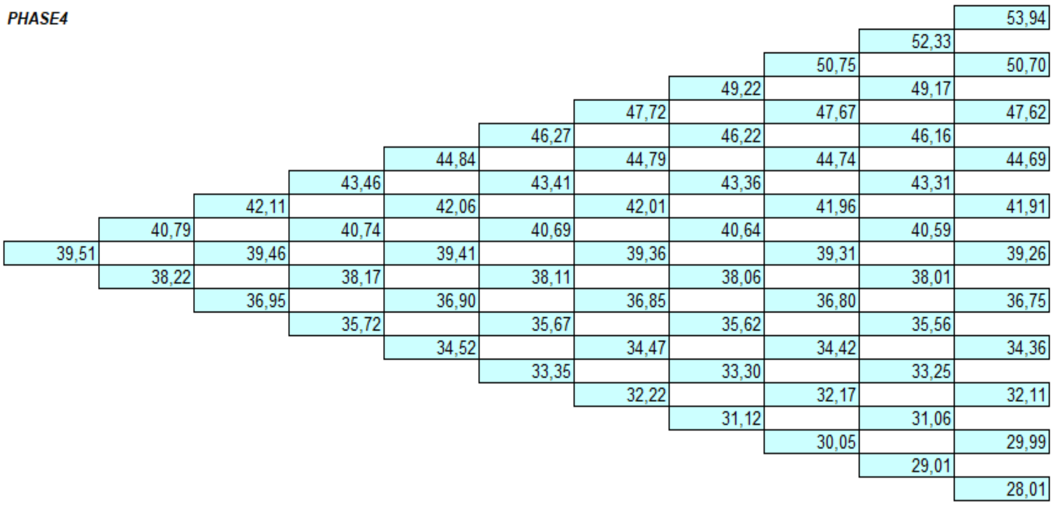

Figure13. *Binomial tree for MPCSCO - phase 4*

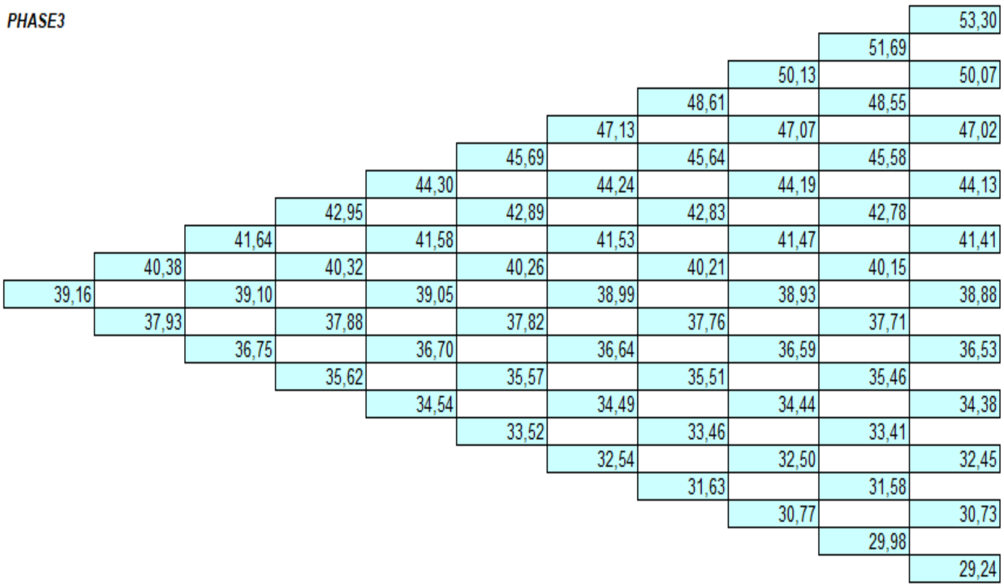

Figure14. *Binomial tree for MPCSCO - phase 3*

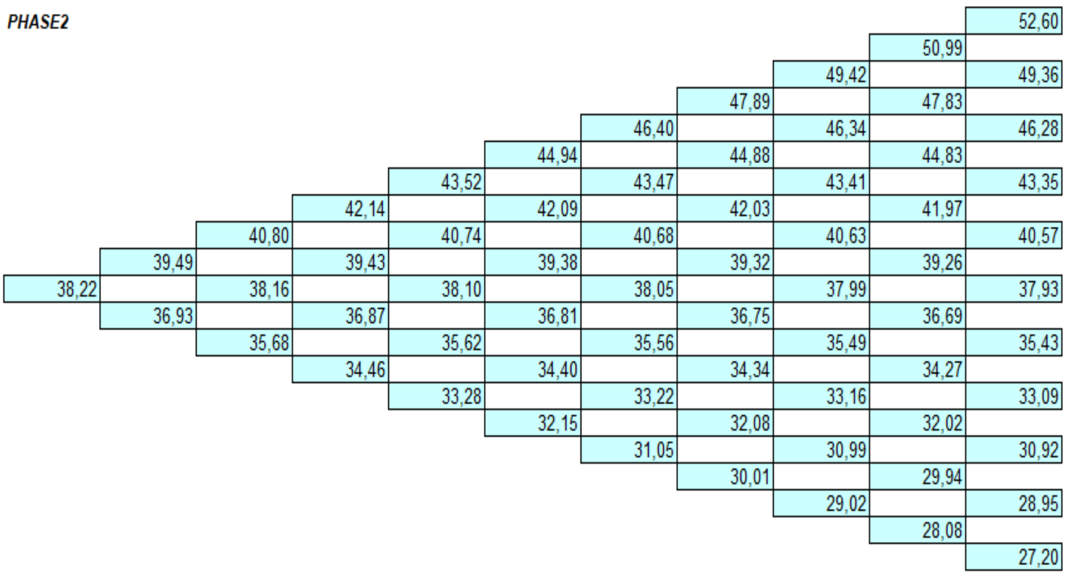

Figure15. *Binomial tree for MPCSCO - phase 2*

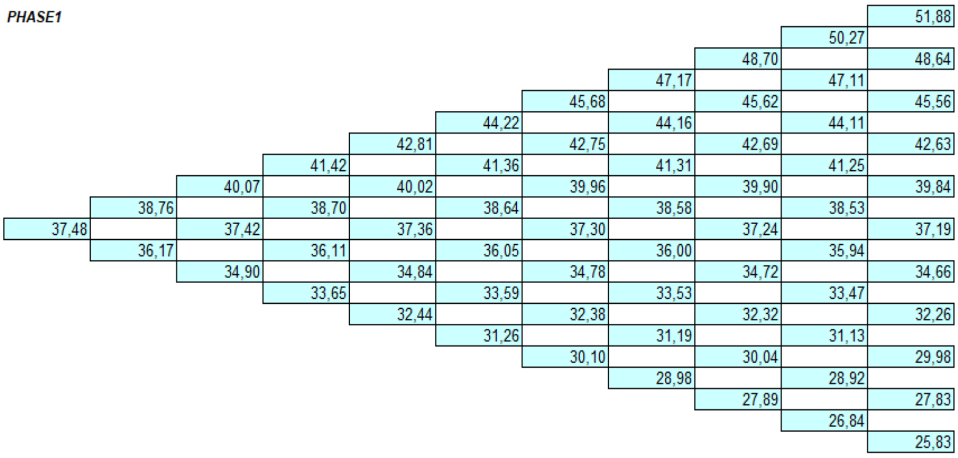

Figure16. *Binomial tree for MPCSCO- phase 1.*

The results of the optimization in this example demonstrated a NPV gain of US$ 0.11 million and a decrease in the variance of the blocks contained in the push backs from 17.95 to 17.85% in the second year of the project. The options entered via ROA added value, except the Option to Abandon. The 50% Option to Expand achieved a gain of US$ 5.00 million, approximately 14.40% of NPV without flexibility. The Option to Contract provided an expanded NPV of US$ 34.88 million with a difference of US$ 0.26 million compared to traditional NPV. And the Multiple Phased Complex Sequential Compound Option presented a gain of US$ 2.83 million, around 8.20% more than the original NPV.

CONCLUSIONS

The uncertainties of ore grade and commodity price have a significant impact on mine sequencing. The mixed methodology for evaluating a mine sequencing project through geostatistical simulation, optimization and ROA, proved to be efficient, adding value to the project. These tools, incorporated into the traditional methodology, proved to be useful.

CONFLICT OF INTEREST STATEMENT

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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