Evaluation of mining projects subjected to economic uncertainties using the Monte Carlo simulation and the binomial tree method: Case study in a phosphate mine in Egypt

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ABSTRACT

Mining project evaluation is a very complex process and time-consuming task. Any mining project passes through several study stages, like conceptual, preliminary feasibility, and feasibility studies, using a systematic and standardized approach. These studies allow investors to evaluate the exploitations alternatives according to economic and technical criteria to make a better decision. This research aims to study a model for investment risk analysis developed for the case study of "Abu Tartur mining project, Egypt." Abu Tartur plateau is rich with phosphate rock, turned into phosphoric acid and fertilizers. This study used site-specific data that has been taken from the literature to build evaluation models using the Monte Carlo Simulation (MCS) and the Binomial Decision Tree (BDT) methods. The Discounted Cash Flow (DCF) is considered a benchmark method for all other evaluation methods. The MCS method uses a set of parameters that, in some cases, will give a higher Net Present Value of the project and some others with lower values, but this depends on the probability of the input parameters. The developed evaluation models allowed a specific range of values, with confidence intervals as the MCS model. The advantage of using a probabilistic approach helps in the decisional phase, allowing for a more precise overview of the variability of the final economic value of the mine. Deterministic methods, like the DCF method, offer solution that is limited to uncertainty analysis.

KEYWORDS: Risk Analysis; Monte Carlo Simulation; DCF; Abu Tartur Plateau; phosphate; Mining; Binomial Tree.

1. Introduction

The mining industry is a very risky activity involving very high capital investment. The decision-makers have to deal with many kinds of risks, from geologic, economic, environmental, and political risks (Dehghani, 2018). Among the others, the primary sources of uncertainty in the mining industry are: (i) the amount of overburden and reserve estimation; (ii) ore grade estimation; (iii) capital and operating costs; (iv) selling prices, (v) recovery ratio; (vi) dilution; (vii) environmental issues. Each parameter should be evaluated and determined by its effects on the project, as investigated by (Topal, 2008) (Dehghani and Ataee-Pour, 2013) (Kopacz et al., 2019).

Each risk should be evaluated, estimated, and determined by its effects on the project and community. The Discounted Cash Flow - Rate of Return (DCF-ROR) (Trigeorgis, 2000) is the most used project evaluation method in mining project evaluation. It is possible to classify it as a deterministic method, while the Monte Carlo Simulation (MCS) (Amico, 2003) and the Binomial Decision Tree (BDT) (Brandao et al., 2005) are classified as probabilistic methods. The mining ventures can be estimated using the Net Present Value (NPV) method (Gardner, 2015). Nonetheless, inputs are unpredictable, and their risks should be identified before estimating the NPV of ore reserves (Erdem, 2008). This kind of calculation does not give any information about the probability of occurrence of the estimated NPV.

Uncertainty and risk management are critical for making decisions in the extraction of mineral resources in a sustainable manner. Uncertainty in mine planning can be evaluated, for example, with a geostatistical simulation of the variables influencing the decision process, which generates a series of equally likely models. Then, for each model, a transfer function is applied. The outcome is a response function distribution that determines the likelihood (or risk) that a particular area meets the product quality requirements. High-risk operations frequently fail to meet ore quality requirements, lowering the value of mineral resources (Kloeckner et al., 2021).

The preliminary investigation stage of any project is known as the pre-feasibility study. The pre-feasibility study is performed to identify, assess, and choose the best business scenarios technically and financially. In this early stage, shortcut methods are permissible and can be applied to determine small investment components and production costs. If the chosen scenario is deemed viable, it is advised that the research be extended to feasibility to gain a more in-depth understanding of the project scenario. In estimating the project's chances of success, a feasibility study considers all the project's essential components, including economic, technical, legal, and scheduling difficulties. It is an engineering study that uses test work and engineering analysis to assess whether or not the project should proceed to the final engineering and construction stage. It is a "go/no-go" decision point, meaning that the answer is sometimes "no" The second difference between these two stages is that once a project has progressed to the detailed feasibility study stage, corporations have typically invested significant resources and built a professional reputation assuming that the project would be practical. Several elements influence whether a project is worthwhile, including the project's cost and return on investment or if the enterprise earned sufficient money or sales from customers (Dou et al., 2020).

The DCF-ROR evaluation method evaluates if a mineral resource can be considered a reserve and, consequently, a mine. It needs a considerable study and works not only a complete assessment and feasibility studies of the deposit but also, needs a complete design and simulation of the mine. If the simulated parameters show promising and positive results, it is possible to exploit the mineral deposit properly. The detailed feasibility study should contain four main fields: economic, financial, environmental, and political studies. Our study will focus on the economic effects due to price volatility and other financial parameters. Political and environmental constraints exist in all countries, especially in Egypt, but they are out of the scope of this research. The economic evaluation of a mining project can be divided into two main quantities, the potential earnings, and the investment costs. If the difference between the two quantities is high enough, the project will be feasible. From the above explanation, the cash flow analysis is defined as the sum of net profit, depreciation, depletion, deferred deduction, and amortization, or the sales revenue minus operating costs and income taxes.

The Binomial Decision Tree (BDT), introduced firstly by (Cox et al., 1979), becomes nowadays one of the most used techniques in economic evaluation, which presents a simple option valuation discrete-time model. The basic economic principles of arbitrage methods for option pricing are apparent in this setting. Its creation involves only basic mathematics, but it includes the well-known Black-Scholes model (Black and Scholes, 1973) as a particular limiting case, historically obtained only from much more complicated methods. In several cases, the basic concept is readily committing itself to generalization. Black and Scholes considered continuous trading and expected stock values to be lognormal distribution. Their approach relied on some very complex mathematics, while it was needed for using a much simpler method (Dehghani et al., 2014). So, a simple option valuation discrete-time model is developed with basic mathematics. It gave rise to a simple and efficient numerical method to evaluate a mining project efficiently (Ganguly et al., 2021) (Azimi et al., 2013) (Ikhsani and Nainggolan, 2021) (Amini et al., 2015) (Dehghani and Ataee-pour, 2012).

MCS is a standard extension of the deterministic NPV base case since it accounts for the possibility that variables are subjected to uncertainty. Generic statistical models classify the input parameters, such as regular, lognormal, uniform, and triangular models. Although it is possible to make associations between variables, they are most generally viewed as separate. In our approach, we will use the MCS jointly with the Black and Scholes time series models (Black and Scholes, 1973) to integrate the association of successive parameter values (e.g., metal price). These expanded simulations of Monte Carlo are somewhat close to those used for the pricing of European options (Kopacz et al., 2017) (Chen, 2011). The duration of the mining project is set in all situations, and the tests provide us with the histogram of potential consequences and the estimated benefit. The fundamental distinction resides in how money's time worth is handled. The discount rate in the deterministic DCF-ROR is called in MCS the "risk-free rate," and in the option pricing method is called "risk-neutral odds of options." The most common method to measure the uncertainty is the sensitivity analysis, while the Monte Carlo Simulation is another way to do that with more consistency (Fontes, Marcelio et al., 2020). Mining project evaluation is a dynamic process, so it needs new evaluation methods, like Real Options Valuation (ROV) (Shafiee et al., 2009).

According to the previous works in mining project evaluation, we found that most economic evaluation is applied to the mineral's ores like Iron, Copper, Gold, etc., which are more valuable, of course (Tleubergen et al., 2017). At the same time, the phosphate ores and other stone ores did not find their way into such models. In this paper, a comparison of the DCF, MCS, and BDT methods is presented and applied to a real case study. We analyze their similarities and differences critically from three points of view: how they treat volatility in parameter values, such as metal price and cost; how they integrate the time value of money; and how they require managerial flexibility. We demonstrate that, given their apparent distinctions, they are simply different features of a general project evaluation system which has its most straightforward type, the deterministic base case scenario. It is worth mentioning that modeling the natural world involves simplification and loss of accuracy. From the general perspective, all three methods can be achieved by dealing with validation elements (Galli and Armstrong, 1999). We emphasized this research as a case study of the (Abu Tartur plateau, Egypt) phosphate mining project.

Among the others, the most important parameters in economic uncertainty are metal price uncertainty and operating cost uncertainty. The NPV was calculated using the three methods (DCF, MCS, and BDT) applied to the Abu Tartur phosphate mining project in four scenarios: (1) assuming certainty for both pricing and operating costs, (2) assuming uncertainty for the price, (3) assuming uncertainty for both price and operational costs, and (4) assuming uncertainty for the price, operational costs, interest rate, inflation rate, taxes' rate, grade, and recovery. When both pricing and operating cost uncertainties were considered, the mine evaluation presented a higher NPV (Dehghani & Ataee-pour, 2012). The evaluation method based on the multidimensional binomial tree method was developed by (Dehghani et al., 2014): the pyramid technique. The NPV has been computed under economic uncertainties to determine the efficiency of the pyramid technique. Finally, the obtained results were compared to the outcomes of other evaluation methods, such as the binomial tree. To the best knowledge of the authors, no previous research performing a comparison between DCF, MCS, and BDT applied to the evaluation of phosphate mining projects with the same four scenarios is present in the scientific literature. Therefore, scenario four is unique, where seven uncertain parameters have been studied. Software to model the binomial tree approach is rare, therefore we developed the binomial lattice algorithm, and it has been implemented and coded in macros in the Excel © environment to build the model. It was a unique effort to handle the problem of the complicated lattice. The price lattice of this mining project has nearly 253 cells and the cash flow and discounted cash flow lattices are as well. In addition, phosphate mining has lacked economic studies. Therefore, with this paper, we contribute a progression to the previous research in the field of mining project economic evaluation.

The paper discusses briefly the nature of phosphate ore chemical composing and its existence in Egypt. Then the developed models have explained in detail the different techniques of mining project evaluation. Results and discussion results are presented, followed by the conclusion.

2. Phosphate ore in Egypt

Phosphates are essential elements for life on Earth (Mitra et al., 2020). Phosphates are used in agriculture, industrial, and chemical process as well. Phosphorous in phosphate form is one of the macro-elements necessary for plant growth (Nitrogen-Phosphorous-Potassium). Farmers have long been concerned with nitrogen fertilizers only for increasing their crops, but with the improvement of agriculture research, it has been established that phosphorus plays a significant role in natural plant growth and therefore increases productivity (Elwageeh, 2017). The growing number of people across the globe implies the growth of the demand for phosphorous.

The world consumption of phosphate rocks is more than 150 million tons per year, where the commercial grade is about 30% of P_2O_5 or higher, as stated (Abouzeid, 2008). Egypt was granted a considerable reserve of phosphates. The Egyptian phosphate ore reserves are usually of low grade, so it needs mineral processing and removing gangue minerals.

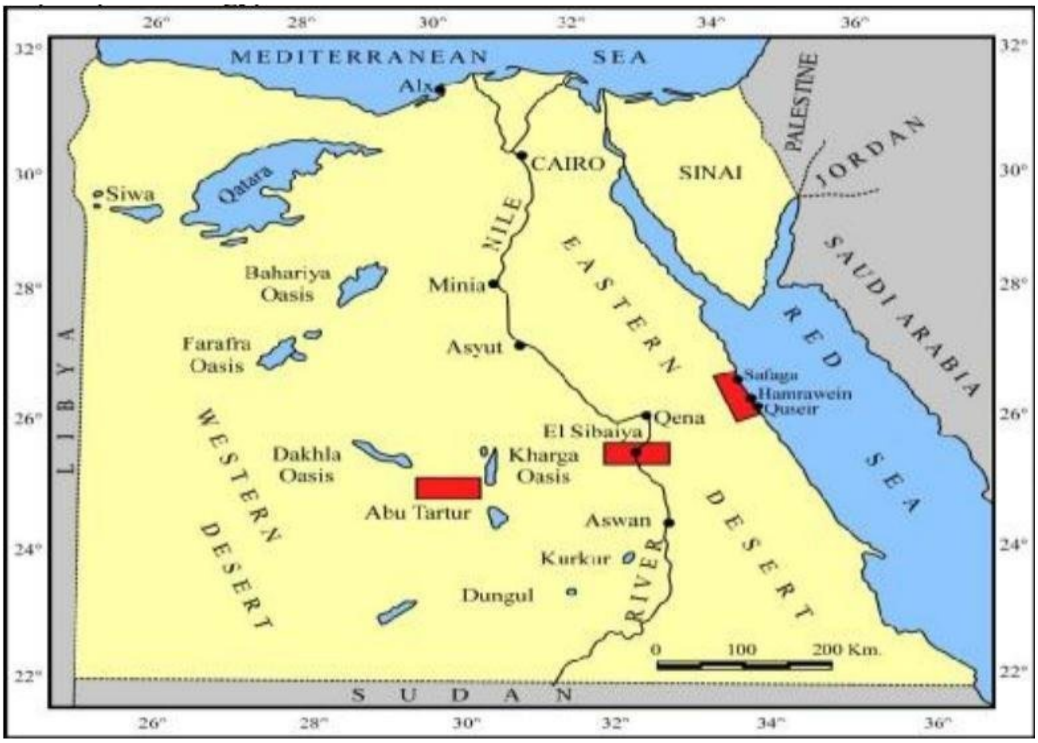


Fig. 1. Location map of phosphorus deposits belt in Egypt, (EMRA, 2021).

Egypt is regarded as one of the world's leading phosphate rock exporters. Nevertheless, by refining this treasure to highly evaluated items, the need to add significant value to Egyptian mineral wealth must be accomplished. The unprocessed Phosphate rock can be used directly in agriculture as soil fertilizer, and the processed mineral can be used in different applications, like pharmaceuticals, personal care products, and polishing agents in toothpaste with calcium. According to (Elwageeh, 2017), Phosphate is composed of apatite and a group of calcium phosphate minerals that is the primary source of phosphoric acid in phosphate fertilizers. Egypt has three main areas of phosphate, which is the belt of phosphate Fig. 1 from the east red seacoast to the New Valley in the western desert. This belt of phosphate is almost of deposition origin.

Abu Tartur plateau lies 50 km west of Kharga City, the capital of the New Valley Governorate in southwestern Egypt. The Abu Tartur plateau is perfectly connected to the urban through a first-class network of a heavy-load asphaltic road. It takes 45 minutes to go from the airport to the mine. The phosphate extracted from the Abu Tartur mine ranges from 24-31% P_2O_5. It is ideal for producing Triple Super Phosphate (TSP), Single Super Phosphate (SSP), Nitrogen Phosphorus and Potassium (NPK), Di-Ammonium Phosphate (DAP), and Mono-Ammonium Phosphate (MAP) fertilizers and direct application. It is as well ideal for producing Phosphoric Acid after using special treatment. It also exhibits significantly low toxic components like As, Cd, Pb, Cr, and Hg. The area of the Abu Tartur plateau is about 1200 km^2, and a raw estimation establishes that the total reserve is more than 5 billion tons of phosphate rock (EMRA, 2021).

The richest phosphate rock in Egypt has been discovered in Sebaiya (Nile Valley), Safaga (Red Sea), as well as Abu Tartur (the Western Desert). The higher the amount of organic matter in the soil, the faster the phosphate rock dissolves. Phosphate rock biological solubilization is more environmentally friendly than acidulation. Phosphate rock injected with bacteria and

Mycrrohizae has proven to be a practical approximation of using phosphate rock for continuous crop production (Hellal et al., 2019).

Mine reclamation is the process of restoring mined land to an ecologically functional or economically viable state. Although mine reclamation occurs after mining is completed, mine reclamation activities are planned before a mine is permitted or started. Liquidation is the process of converting assets into cash or cash equivalents by selling them on the open market. An asset is a value-added component in finance. In our case study, the reclamation and liquidation costs are not considered in the NPV calculations, therefore it is recommended to reassess the project implementing these costs.

3. Methods

The mining project evaluation process involves uncertainty. The economic evaluation of mining projects can be classified into four scenarios. The First scenario uses Parameters With Fixed Values (PWFV). These values are considered “trusted values” that have been known before from the first stages of the pre-feasibility and feasibility studies (Barnes, 1980). Therefore, the economic evaluation process will use the DCF method. The second scenario assumes one uncertain parameter, while the others are fixed as the first scenario which is the ore price. In this scenario, the representation model is the BDT model. The third scenario assumes two uncertain parameters, and the MCS method is the most common method used to deal with this kind of problem. The fourth scenario of the evaluation process implements seven uncertain parameters to the evaluation model using the MCS method.

The deterministic method, like the DCF-ROR, uses the input parameters as PWFV. The BDT method mainly depends on predicting mineral price and operating cost parameters. Prediction means that we know the present value of such parameters and need to know its value in the future and, in turn, predict its effect on the NPV, the Internal Rate of Return (IRR), and the Payback Period (PP). On the other side, the MCS will also start from present values, but it will depend on the distribution of such parameters according to the variable nature of the parameters. This makes turbulence of parameters like price (Dehghani and Bogdanovic, 2018) reverse the investment from profit to loss. So, the MCS technique is beneficial for decision-makers. MCS has been used in this study to evaluate the NPV value considering parameter uncertainty (Mohapatra, 2009).

3.1. The Net Present Value approach (NPV)

The NPV must be computed to assess the value of the mine. In DCF, the most popular approach is NPV, BDT, and MCS. NPV is defined as the cash inflow discounted to the present minus the investment cost. According to Eq. (3), the NPV shows the initial capital cost and the discounted cash flow. So, the NPV is defined as the difference between the present value of cash inflows and the present value of cash outflows over some time. NPV is used in capital budgeting and investment planning to analyze the profitability of investment projects. NPV is the result of calculations used to find today’s value of a future stream of payments and costs. Most decision-makers utilize a single-figure output to determine the project's financial worth. However, the NPV should always be calculated based on the project's financial scale. There are two types of expenditures Operating expenses (OPEX) and capital expenditures (CAPEX) that a company incurs on an ongoing basis.

CAPEX is a company's major, long-term expense, whereas OPEX is day-to-day costs. Equipment, machines, and trucks are examples of CAPEX. Overhead expenses such as wages, utilities, and property taxes are all examples of OPEX. For tax purposes, capital expenditures cannot be deducted from income, whereas operating expenses can (Chen, 2021). Companies should be cautious about investing in projects with high CAPEX and OPEX but only a moderately positive NPV.

To calculate the NPV, the analyst should discount the future cash flow in addition to the investment cost, as shown in Eq. (3). The Cash Flow is calculated through Eq. (1) and Eq. (2):

$$X_t = (P_t - C_t) \times Q_t - F_t - D_t \quad (1)$$

$$\left\{ \begin{array}{ll} CF_t = X_t(1 - T_t) + D_t & \text{if } X_t > 0 \\ CF_t = X_t + D_t & \text{if } X_t \leq 0 \end{array} \right\} \quad (2)$$

Where:

X_t: taxable income at time t
P_t: price at time t
C_t: operating cost at time t
Q_t: tonnage of production at time t
F_t: fixed cost at time t
D_t: the deprecation at time t
CF_t: cash flow of the project
T_t: tax rate at time t.

$$NPV = -CI + \sum_{t=1}^{n} \frac{CF}{(1+i)^t} \quad (3)$$

Where:

NPV: is the net present value.
CI: is the capital investment.
CF: is the cash flow.
t: is the time in years.
n: is the project lifetime.
i: is the discount rate.

3.2. The Discount Cash Flow method (DCF)

The classical deterministic method of economic analysis of a mining project is the Discounted Cash Flow (DCF), derived by (Fisher, 1930). DCF is the most reliable and popular method with three main measures NPV, IRR, and PP.

The DCF analysis is commonly used to estimate the discounted potential cash flows over the project life to get its present value. The PWFV is applied, so uncertainty and risk are not represented. The economic study's main aim is to help investors understand the estimated present value of the potential profit and expenses relative to the investment's costs (Stermole and Stermole, 1999).

3.3. Monte Carlo Simulation method (MCS)

The MCS method is designed to model the likelihood of various outcomes in a procedure that cannot be easily forecasted due to random variables. It is a method used in statistical and forecasting models to study the effects of risk and uncertainty (Brandimarte, 2014). A random value is chosen from a given range between min. and max. For each input parameter. These values are involved in the equation of the NPV computation. A standard simulation in MCS calculates many solutions, using different parameter values chosen each time randomly. When

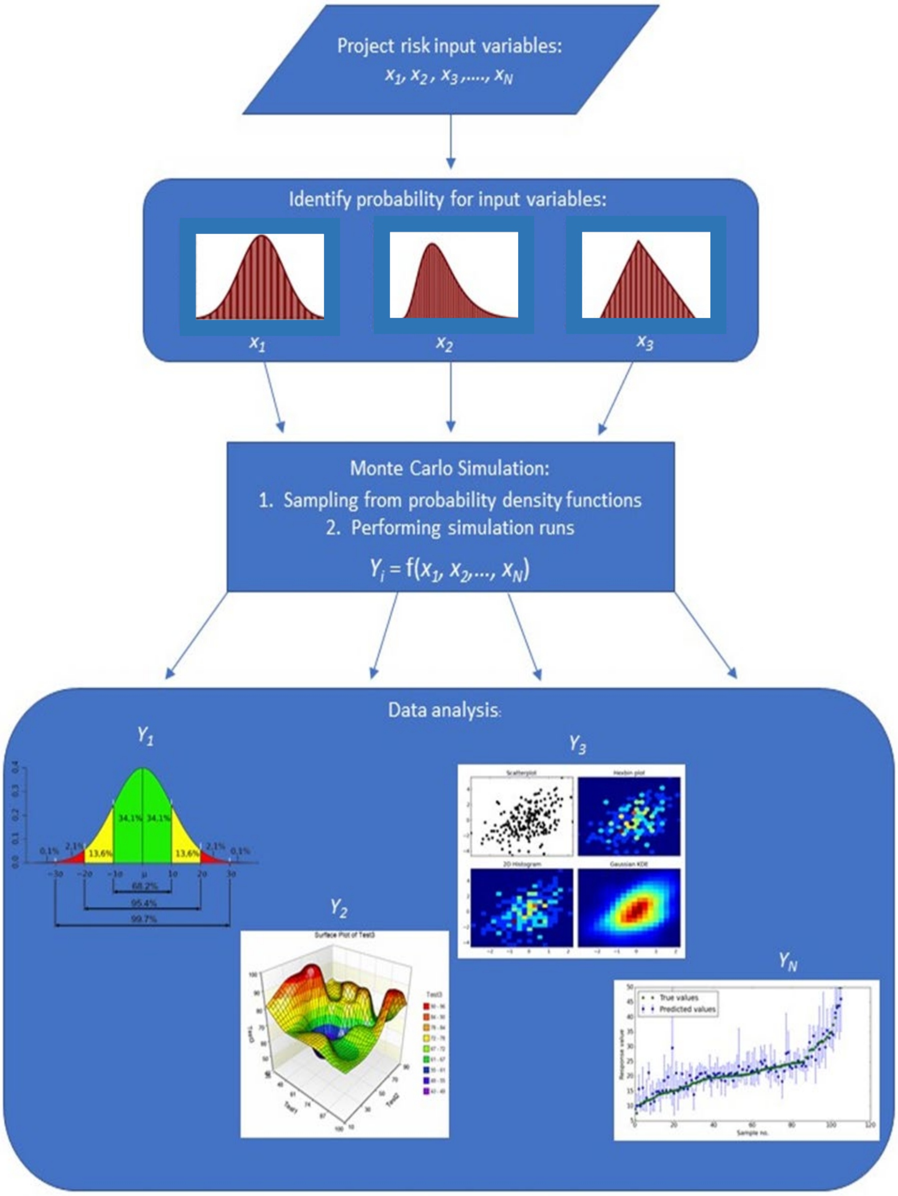


Fig. 2. The procedure of Monte Carlo Simulations from input to output (NASA, 2017).

the simulation is completed, as indicated in Fig. 2, we have many model outputs, each dependent on random input values. These results are used to characterize the probability of the model producing different outcomes (Samis and Davis, 2014), (Gamba, 2005) (NASA, 2017).

3.4. The Binomial Decision Tree method (BDT)

The binomial model is a well-known, discrete alternative time developed by (Cox et al., 1979). The BDT is a graph structure that maps all possible metal price trajectories over time, as the model permits calculating the NPV approach. The structure is made up of nodes and branches. Each node in each layer corresponds to a possible metal price at a specific point in time. Nodes are marked with both traversal probabilities and metal prices. A convenient indexing scheme has the layer or time level defined by j (number between 1 and n, number of layers or time steps), and the nodes within each layer (possible metal prices) by i (number between 1 and m, number of nodes in the layer). The node count m for any given layer will range from j to twice the number of nodes in the previous layer, depending on whether the tree is recombining or not. Each branch or path in a binomial pricing tree represents a potential transition from one node to another later in the tree and is associated with a likelihood and a ratio. Higher node connections represent probabilistic value (P_0) and up factor (u), whereas lower node branches represent probabilistic value (P_0) and down factor (d). Fig. 3 shows a schematic binomial tree with three measures on the first metal price at time zero (P_0). The factors up (u) and down (d) and the likelihood of occurrence (Pr) were calculated using the following formulation (Dehghani, 2018)(Brandao et al., 2005).

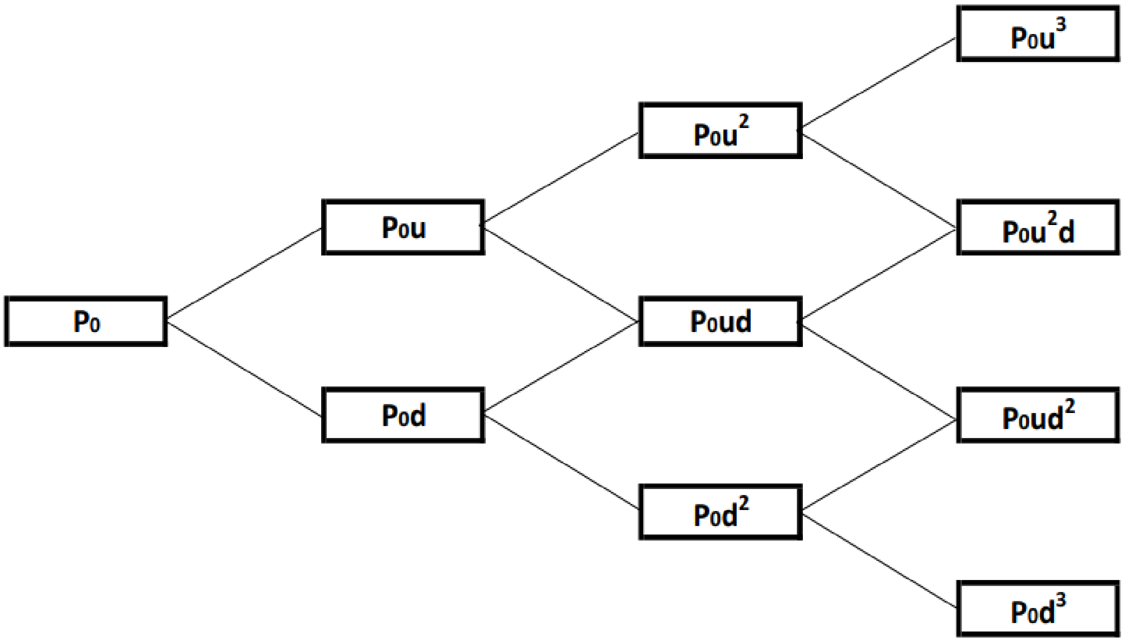


Fig. 3. Three-time step binomial tree

$$u = e^{\sigma\sqrt{\delta t}} \quad (4)$$

$$d = e^{-\sigma\sqrt{\delta t}} = \frac{1}{u} \quad (5)$$

$$p_r = \frac{(1+r)-d}{u-d} \quad (6)$$

The volatility of the metal price (σ), the risk-free rate (r), and the stepping time (δt) are the primary inputs. In evaluating the proposed Abu Tartur area project, we select three different scenarios, assuming a combination of deterministic and probabilistic parameters.

3.5. Computation methods

To evaluate the feasibility study of a hypothetical phosphate mine project, we implemented several Excel worksheets for the three presented methods, DCF, BDT, and MCS method. From a computational point of view, the DCF method is quite simple and easy to implement. The BDT algorithm complexity has been implemented using the Visual Basic for Applications (VBA) programming language in an Excel environment. The MCS method has been applied to our scenario using the software (@Risk, Crystal ball).

In the following, we compute the pre-feasibility study using the deterministic and probabilistic methods, as presented in Table 1.

Table 1
Computation methods assumptions

Computation method number	Comp. Method	Variable's type	Variable's uncertain assumptions
1	DCF	deterministic	None
2	CF, BDT	deterministic and probabilistic	ore price
3	MCS	deterministic and probabilistic	ore price and operating cost
4	MCS	probabilistic	ore price, operating cost, grade, recovery, ROR, inflation rate, and taxes rate

In computation method 1, we assumed deterministic metal price and operating cost. In this way, we can estimate the DCF value of the mine. The purpose of these calculations is to make investors aware of the expected present value of future cash flows compared to investment costs. Eq. (1), Eq. (2), and Eq. (3) can be used to get the base case NPV.

In computation method 2, it is considered that metal price is uncertain using the Binomial Decision Tree (BDT). A binomial tree is constructed depending on the historical data and Eq. (4), Eq. (5), and Eq. (6). It is the method to forecast future prices. The future operating cost data is determined using regression analysis depending on the inflation parameter. So, a new Cash Flow (CF) binomial tree is estimated depending on the previous lattice, annual estimated operating cost, and Eq. (1) and Eq. (2). Finally, the CF is discounted in another tree that is constructed. The DCF will be estimated using Eq. (7) and opposite the previous lattices (from right to left).

$$\mathrm{DCF}_{t,k} = \mathrm{CF}_{t,k} + \frac{p_r \times \mathrm{DCF}_{t+1,k} + (1-p_r) \times \mathrm{DCF}_{t+1,k+1}}{(1+r)} \quad (7)$$

Where k is the node number at time t.

In computation method 3, the price and operating cost have been assumed as uncertain parameters, while the other parameters are PWFV. For each parameter, a probability distribution is chosen depending on historical data. A close fit to the distribution is supposed to result in good predictions. In distribution fitting, it is necessary to use a distribution that is well-suited to the data. The project evaluation is obtained by the MCS method.

In computation method 4, all dynamic input parameters are uncertain, including (price, operating cost, grade, recovery, interest rate, inflation rate, and Taxes rate), while the other parameters are PWFV. After the global economic crisis in 2009 and the revolutions that occurred in Egypt in 2011 and 2016; Egypt has floated its currency in a move that has reduced its value by almost 50% against the USD dollar in 2016. The Egyptian Central Bank considered this move as one of a list of reforms designed to strengthen confidence in the economy. The Central Bank has also increased interest rates by 3% reaching 14.75%. Therefore, we aimed to study the effect of variability of the interest rate by using a probability distribution.

The proposed method of project estimation that consider the variable uncertainty is the MCS. To perform the MCS, the first step is to develop an analytical model to be evaluated. The second step is to generate a probability distribution for each variable of the model, using subjective or historical data. The MCS model computes the outcomes of the project using the statistical distribution of all the parameters in the NPV equation. The statistical distributions, such as normal, lognormal, triangular, and uniform, are used to evaluate the project considering the uncertainty in parameters. We used the statistical distributions of the variables according to the available data and we assumed the statistical distribution of parameters for variables with poor information. In every simulation, the values are selected randomly from each parameter distribution for every period and substituted into the NPV equation to generate one possible outcome of the project. We noted that the price and operating cost had identical distributions and values as in scenario 3. Finally, many model outcomes are generated, and a corresponding model of probabilities vs. model outcomes is generated.

4. Results

This study investigates the uncertainty of prices and costs of the ore and the equipment.

4.1. Input Data

The input data that have been used in this work are literature data from (Elwageeh, 2017). In Table 2, a resume of the technical parameter is reported. The Phosphate average grade (30%) and the cutoff grade (25%) improve the company's profit (Afify and Zaghloul, 2014) (Hellal et al., 2019). The stripping ratio is defined as the amount of overburden that should be removed to extract a given ore quantity. The hypothetical mine life is determined by dividing the reserve tonnage at the cutoff (million tons) (Azimi et al., 2013) over the ore production rate planned (million tons/year), which gives 22 years for the production rate of 3.5 million tons/year. Table 3 is resumed the financial parameters used in this study.

Table 2
Technical parameters related to mine

Technical Parameters	
Average Grade	30.0%
Cutoff Grade	25.0%
Reserve Level at Cutoff (million tons)	77.50
Contained Value (million tons of P_2O_5)	23.25

Stripping Ratio	8.5
Ore Production Rate (t/d)	11,667
Mill Recovery	95.0%
Operating days/year	300
Mine Life (year)	22
Ore Production Rate planned (million tons/year)	3.50

Table 3
Financial parameters

Financial Parameters	
Average (HPO4) Price ($/t)	766.0
Mine Operating Cost ($/t)	15.0
Mill Operating Cost ($/t)	45.0
Total Operating Cost ($/t)	60.0
Mine Capital Cost ($)	580,000,000
Mill Capital Cost ($)	800,000,000
Total Capital Cost ($)	1,380,000,000
Working Capital ($)	60,000,000
Capitalized Exploration Cost ($)	1,000,000
Depletion Allowance (%)	15.0%
Royalty (% Net Smelter Return)	5.0%
Income Tax Rate (%)	46.0%
Salvage Value (% of Capital Costs)	10.0%
Real Risk-adjusted Discount Rate (ROR) (%)	10.0%
Inflation (%)	3.0%

4.2. Output Data

For computation method 1, considering the deterministic metal price and operating cost, Fig. 4 represents the relation between NPV and DCF-ROR. The figure indicates that the NPV decreases with an increase in the ROR. We notice that, at DCF-ROR=0%, the NPV is $9.5 Billion, which is an impossible case, of course. While at DCF-ROR 24%, NPV vanishes (i.e., NPV=$0), and in this case, the DCF-ROR is called the IRR. By increasing the ROR more than the IRR limit (24%), we obtain a negative NPV which means that a risk case benefits the mining project.

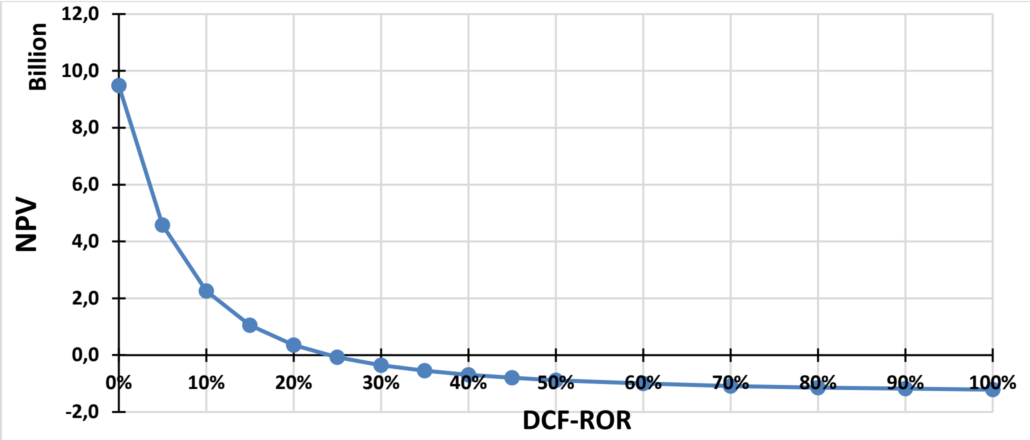


Fig. 4. The relation between net present values (NPV) versus DCF-ROR.

The NPV, IRR, and payback period are presented in Table 4. The NPV, calculated at a 3% inflation rate and 10% rate of return, is estimated at $2.25 billion. NPV is a positive value which is a good indication for the project. The second measure is the IRR; in our case, we get nearly 24% greater than the introductory rate ROR=10%. It is also a good indication and confidence in our progress in the project's evaluation process. The payback period is estimated at five years, less than a quarter of the project's lifetime (22 years). So, it is a very positive duration for payback.

Table 4
Results from the DCF-ROR method.

Results	
Average NPV ($)	2,258,968,007
IRR (%)	24.00
Payback Period (years)	5.0

Computation method 2 (uncertain metal price) is used to predict the mineral price and calculate the free cash flow, the DCF, and the NPV. Each of them has its decision tree and equations. So, in this scenario, one of the input data is of uncertain value while the others are PWFV; this parameter is the ore price.

Table 5 contains the input data for each decision tree described previously. The first price in the price tree is 766 $/ton, which is used in the model of DCF. Volatility (σ) represents the change rate of historical price data. In the BDT method, the risk-free rate of return is the theoretical rate of return of an investment with zero risk. In a risk-free investment, the risk-free rate is the interest an investor would incur over a specified period of time. The so-called "real" risk-free rate can be calculated by subtracting the current inflation rate from the yield of the treasury bond matching the investment duration.

Table 5
Input parameters related to price for the BDT method and BDT-NPV result.

Input data	
Volatility (σ)	28.5%
Up (u)	1.33

Down (d)	0.75
Risk-free rate (rf)	7%
Stepping time (t)	1.0 year
Probability (P_r)	55%
First price in the Binomial lattice (P_o)	766$/ton
Average NPV	**$2,126,849,233**

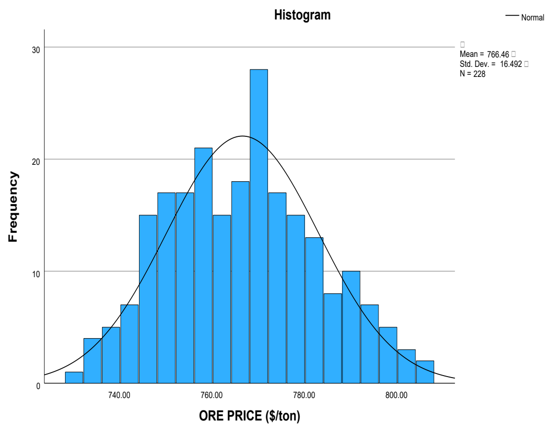
The parameters for the computation method 3 are reported in Table 6 and Fig. 5. It assumes a distribution function for parameters subject to uncertainty. Table 6 reports the basic statistics and the histogram for the seven parameters used in calculations. The historical data for the seven parameters have been analyzed and the statistical distribution has been assumed using the best-fitting theoretical distribution. The model of MCS generates random numbers from the range (0-100%) for all parameters of the theoretical statistical distribution, then applied in Eq. (1), Eq. (2), and Eq. (3) to get the NPV value. This process has been repeated 10000 times and finally, was possible to generate the probability distribution of the NPV.

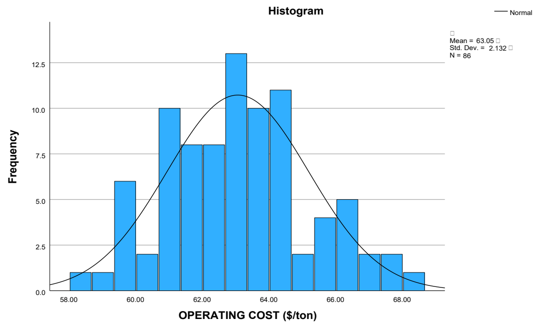
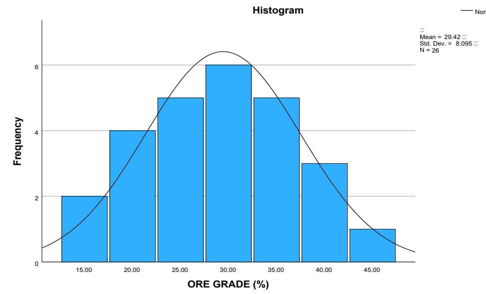
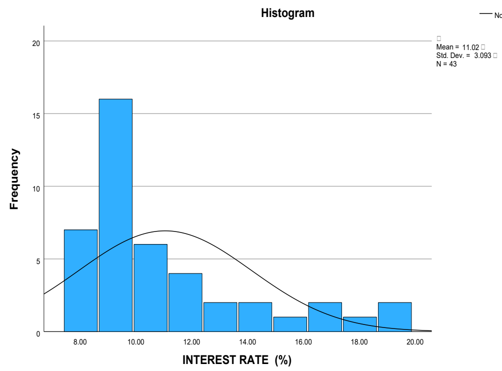
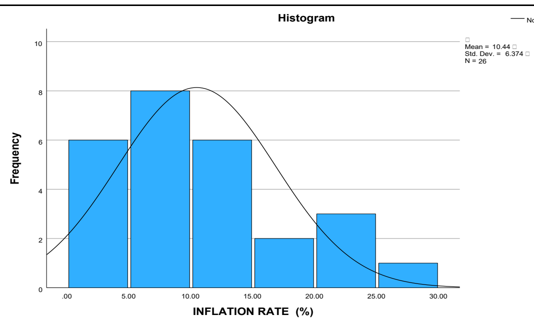
Table 7 shows the correlation matrix between the input variables which is an important factor to consider in Monte Carlo simulation. When the input random variables are considered independent, the uncertainty can be underestimated or overestimated. In the case of a positive correlation, the value for each should be relatively high in one simulation iteration and relatively low in next simulation. For negatively correlated inputs, one variable should be at the high end of the possible range for a given iteration, while the other should be at the low end. In most cases, the variables are assumed to be independent to simplify the calculation. In reality, the majority of the variables are frequently correlated. In mining, for example, ore grades are positively correlated with ore recovery. In addition, it is shown that the prices and operating costs are correlated with the inflation rate.

Table 6

Input data about phosphoric acid in the MCS technique.

Parameter	Distribution	Mean	Standard Deviation	Skewness	Kurtosis	Histogram of the parameter
Average Price	Normal	766.5 $/ton	16.5 $/ton	0.186	-0.521	



<table>
<tr><td>Operating Cost</td><td>Normal</td><td>63 $/ton</td><td>2 $/ton</td><td>0.182</td><td>-0.207</td><td>
</td></tr>
<tr><td>Average Grade</td><td>Normal</td><td>29.4 %</td><td>8 %</td><td>0.121</td><td>-0.756</td><td>
</td></tr>
<tr><td>Interest Rate</td><td>Log-Normal</td><td>11%</td><td>3%</td><td>1.315</td><td>0.619</td><td>
</td></tr>
<tr><td>Inflation</td><td>Log-Normal</td><td>10.4%</td><td>6%</td><td>0.895</td><td>0.143</td><td>
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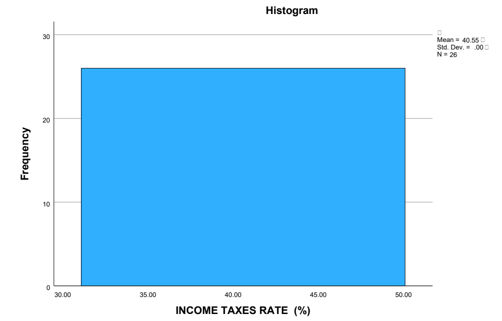
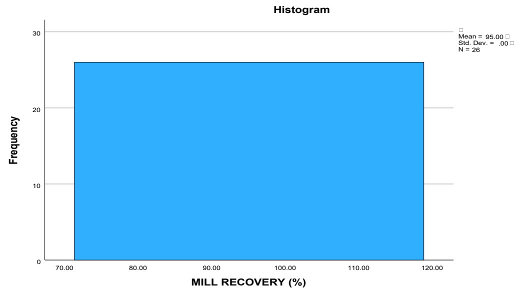
Income Tax Rate	Uniform	44.55%	0%	-	-	
Mill Recovery	Normal	95%	0%	-	-	

Table 7
Correlation index between input data in the MCS technique.

Parameter	Average Price	Operating Cost	Average Grade	Interest Rate	Inflation Rate	Income Tax Rate	Mill Recovery
Average Price	1.0	-	-	-	-	-	-
Operating Cost	0.77	1.0	-	-	-	-	-
Average Grade	0.80	0.50	1.0	-	-	-	-
Interest Rate	-0.45	-0.22	0.03	1.0	-	-	-
Inflation Rate	0.94	0.88	0.28	0.80	1.0	-	-
Income Tax Rate	0.66	-0.40	-0.08	0.01	0.01	1.0	-
Mill Recovery	0.30	0.60	0.05	0.01	0.01	0.01	1.0

Due to the character of this preliminary feasibility study of the mine project, the statistical distribution of variables has been fitted to the histogram distribution. The mean and the standard deviation have been used to define the variable distribution in the Crystal Ball software. The mean values are corresponding to values used in scenario 1, for all the parameters. The statistics of data have been estimated using SPSS software (Farahani and Bayazidi, 2018) from the historical data fluctuation for those parameters (AFA, 2021). Depending on the characteristics of the phenomenon and the distribution, some probability distributions can be fitted more closely to the observed frequency of the data rather than others. The distributions of the discount rate, income tax, and inflation parameters are taken based on the official websites of the Central Bank of Egypt (Egypt, 2022a), the Ministry of Finance of Egypt (Egypt, 2022b), and the Central Agency for Public Mobilization and Statistics (Egypt, 2022c). These parameters are distributed according to the guidance values published on such websites, and they were considered unrelated.

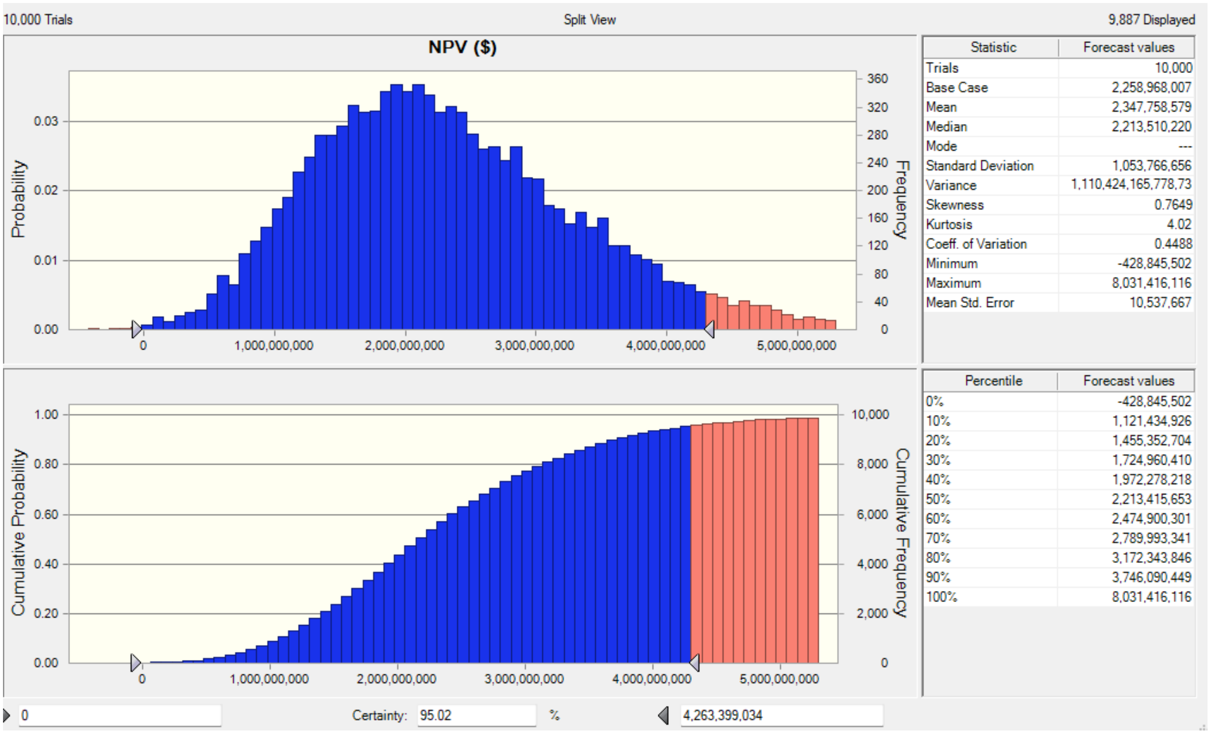


Fig. 5. Statistical distribution of NPV and its parameters for scenario 3.

Fig. 5 represents the results of the computation method 3. It reports the NPV as a function of the parameter's probability. It indicates that the mean value of MCS is near the base case, under the effect of uncertainty in the parameters (price and operating cost). The graph reveals that for the uncertainty of the input parameter of 50 % (Median value), the expected value of the NPV was 2.35 billion dollars. If we consider a confidence interval of 95%, the expected value of the NPV will be between (0.00-4.26) billion dollars.

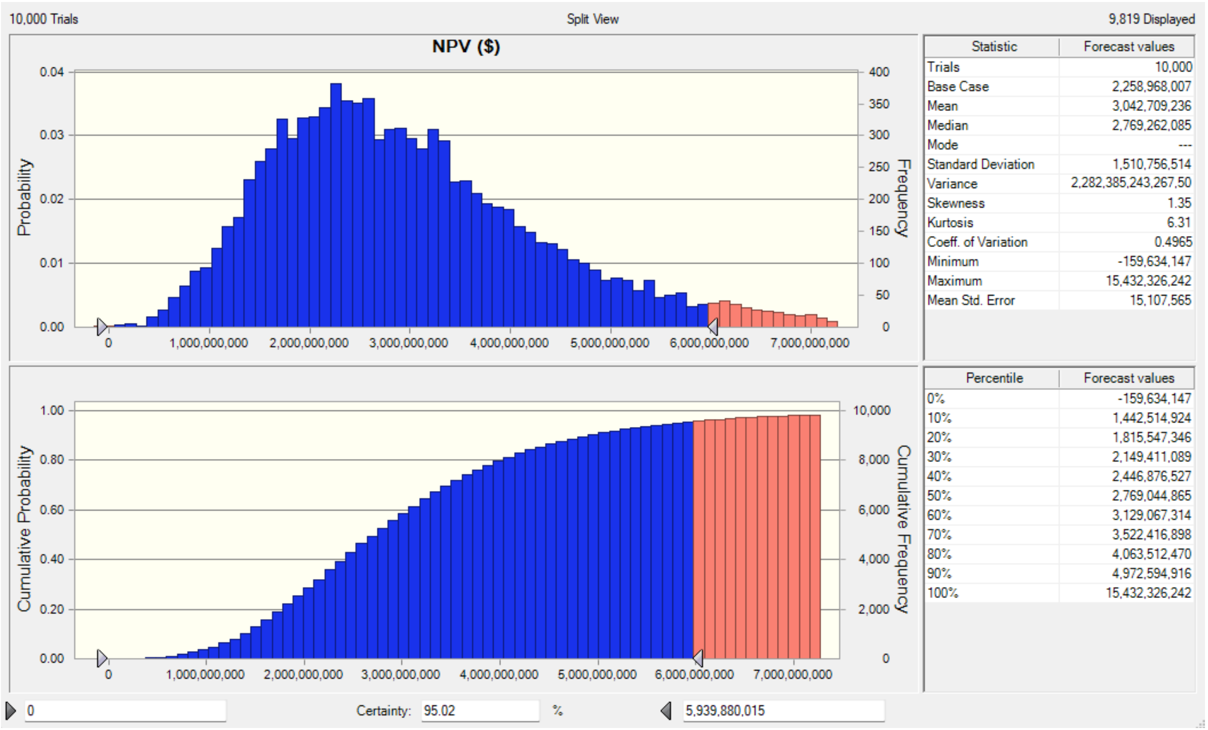


Fig. 6. Statistical distribution of NPV and its parameters for scenario 4.

Computation method 4 is represented in Table 6 and Fig. 6. It considers the case in which most input parameters are subject to uncertainty. As shown in Table 6, we have seven parameters under the effect of uncertainty. Fig. 6 shows the results of the MCS run obtained using 10000 iterations. The graph reveals that for the uncertainty of the input parameter of 50 % (Median value), the expected value of the NPV was 3.04 billion dollars. If we consider a confidence interval of 95%, the expected value of the NPV will be between (0.00-5.94) billion dollars. In MCS, assuming that the ore price, operating cost, grade, and other parameters are subjected to uncertainty, the NPV is calculated considering uncertainty and offers more realistic values, than the other methods. As shown in Fig. 6, the distribution of the output of the NPV is lognormally skewed to the left. This effect comes from considering the lognormal distribution of some variables used in the simulation.

5. Discussion

The DCF method deals with technical and financial parameters in a deterministic manner. BDT technique handles the parameters uncertainty with a discrete probability for each node, but the tree becomes exponentially larger with increasing the time step compared to the mine life. The MCS was better than the DCF and the BDT methods of handling the uncertainty using continuous distribution for technical and financial parameters.

The DCF method assumes that the scenario used PWFV, so the decision-maker cannot have a clear overview of the final results of the parameter change. The BDT method deals with different strategies and shows all the probable outcomes for the NPV obtained from these strategies. The MCS method focuses on modeling the uncertainties and neglects managerial flexibility, but it shows the distribution of the NPV before starting the project.

MCS is a natural extension for the base case of NPV since the variables are not known with certainty. These variables are described using statistical distributions such as normal, log normal, and uniform distribution. Although it is allowed to make correlations between variables, they are viewed as independent. In MCS, the project life is fixed in all cases, and the results have the histogram of future results and the expected value. The underlying distinction lies in how the time value of money is treated. In the BDT method, the maximum expected value is estimated by folding the tree back from the outer end branches toward the start. They have some characteristics such as: (i) how they handle the time value of money (discount rate vs. risk-free rate plus change of probability), (ii) how they allow for uncertainty in parameter values, and (iii) whether they incorporate managerial flexibility.

Scenario 1 indicates that using the PWFV, the mine project is feasible. Scenario 2 considers the variability of the mineral price, indicating that in some cases, the project is not feasible, and in others, the NPV is greater than the NPV obtained by Scenario 1. Scenarios 3 and 4 allow for obtaining similar results, with the added value to give jointly with the NPV a measure of the probability of success of the mining project. In addition, the MCS method allows re-generating during the mine exploitation by updating the random used values with the actual values, allowing for back analysis.

Table 8
Summary of the results.

Case No.	Average NPV (B $)	Change of the base case	Confidence Interval	Notes
Scenario 1	2.26	0%	0%	DCF (Base Case)
Scenario 2	2.13	-6%	<50%	BDT (uncertain mineral price)
Scenario 3	2.35	4%	95% (0-4.26 B$)	MCS (uncertain price and operating cost)
Scenario 4	3.04	34%	95% (0-5.94 B$)	MCS (uncertain multi-input parameters)

Table 8 shows the NPV obtained using the four different computation methods. The reference case was the DCF method, which used the deterministic value of the technical and financial parameters. These parameters mainly come from the feasibility and pre-feasibility studies made on the project. According to the computation of the NPV, it was estimated that NPV was $2.26 billion, which is an encouraging value (NPV>0) for the feasibility of the project. The IRR was 24%, which is an encouraging result as well. Encouraging results for mining projects are considered when IRR>ROR10%. Finally, the computed payback period was five years. So, it is also fine because the Payback Period is less than the mine life, which was established in 22 years (as in Table 2).

The second scenario has been computed using the BDT method. The average value for this scenario was NPV=$2.13 billion, which is lower than the reference case of the DCF by -6%.

The MCS technique for the third computation method was obtained considering the uncertain mineral price and operating cost parameters. Results show that the NPV was higher than the reference scenario by 4%, which is a good evaluation result of the method.

The fourth scenario worked for seven uncertain parameters using the MCS method. Results show that the computed average of the computed NPVs was higher than the reference scenario by 34%. The confidence interval was higher in scenarios 3 and 4.

These project evaluation results were hopeful and can encourage the investor to consider the mining project with more confidence. Fluctuations of the ore price and the cost are not represented in the deterministic method, while in the probabilistic methods they are taken into consideration. Therefore, the MCS method can study thousands of trials or scenarios that may happen in the real world and give the probability of the results and their confidence intervals value. The MCS can consider the real-world parameter variability, in order to compute thousands of scenarios and compute the probability of the obtained NPV. The issue here is how to represent the parameters well so that we can evaluate the project accurately. In our case study, we found that the project is profitable from the DCF calculations, but what if the price decreases, and what if the cost increases? The sensitivity analysis or what-if analysis can answer these questions for limited cases and limited parameters. The MCS aims to consider these problems, therefore we can represent the fluctuation of multi-parameters in one model and at any stage of the project.

6. Conclusion

The work aims to assess phosphate mining project scenarios in the Abu-Tartur region, Egypt. Different methods have been used to estimate the NPV, IRR, and PP in the present work. The latter parameters have been computed using different computation methods under various scenarios. Discounted Cash Flow (DCF) is commonly used to evaluate mining projects, while other methods like Binomial Decision Tree (BDT) and Monte Carlo Simulation (MCS) enable the decision-maker to evaluate the project clearly and consider the risk in the project due to uncertainty in parameters. Finally, the BDT method results in a specific value of NPV depending on the probability of input parameters. We can conclude that the MCS method is favorable compared to other methods. The MCS method applies a set of parameters that, in some situations, produce better results than others, although this is dependent on the likelihood of the input parameters. It is the best way since it aids in considering the uncertainty of the parameters and variability assessment and determining which parameters greater influence the outcomes.

In order to consider uncertainty, the distributions of the input variables were tested for goodness of fit with the observed data using histograms. The parameters of the normal, lognormal, and uniform distributions, i.e., the mean and standard deviation were also calculated from the data for each variable. The MCS for project evaluation overplays the importance of the choice of which distribution to use to represent input variables and underplays the importance of assessing and including correlations between the variables. Simulation runs of the evaluation model including correlations showed that correlations must be included in Monte Carlo Simulation otherwise the analysis leads to an underestimate of risk. It is relatively more important to investigate and allow correlations between the variables than to select the best fit distribution to represent the parameters in the MCS.

The MCS technique allows to improve project estimation and comprehension of the variability of the results. So, the MCS method allows for a better estimation of the project and an understanding of the variability of the results. Real validation of the proposed method will be possible when the mining project will start. Future work can consider a comparison of the results obtained in this study with other project evaluation emerging methods, like the Real option Valuation and Cash Flow at Risk (Sauvageau and Kumral, 2018), as well as considering the liquidation/ reclamation cost of the project and the mineral grade modeling using, for example, geostatistical methods.

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