

A model for quantification of environmental risk in mining ventures

Modelo para quantificação de risco ambiental em empreendimentos de mineração

Un modelo para la cuantificación del riesgo ambiental en empresas mineras

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ABSTRACT

The premature termination of industrial projects, often triggered by insufficient revenue generation to cover liabilities, poses a significant challenge in project evaluation. Although the conventional discounted cash flow (DCF) method remains widely used, its inability to account for project failure probabilities can lead to resource misallocation. This study aims to address this limitation by applying real options theory to assess the risk of premature abandonment within the context of a mineral extraction project. In this proposed system, fluctuations in environmental remediation costs are modelled by considering the cumulative probabilities of cost increases or decreases at each time step. The simulated project value reflects the cumulative activities required for mine closure, where each ton of extracted ore generates an environmental liability demanding remediation. Through the application of this system, the study demonstrates its effectiveness in identifying an escalating probability of project closure over time. Particularly, the findings reveal the existence of a critical threshold date. Beyond this date, any operational suspension exceeding one year renders project closure the economically optimal choice. This closure encompasses all necessary environmental restoration activities. By integrating real options theory into project evaluation, this study offers a more comprehensive approach to assessing the risk of premature project abandonment in mineral extraction projects. Through the consideration of fluctuating environmental remediation costs and the cumulative probabilities of project closure, it provides valuable insights for decision-making in project management and resource allocation. The trigger curve generated allowed for the identification of the viability threshold of the venture. Identifying the threshold to initiate the mining closure project.

Keywords: Environmental Reclamation. Mine Closing. Natural Underground Cavities. Real Options Theory. Theory Of Discounted Cash Flow.

RESUMO

A conclusão prematura de projetos industriais, muitas vezes desencadeada por uma geração de receitas insuficiente para cobrir as responsabilidades, coloca um desafio significativo na avaliação dos projetos. Embora o método convencional de fluxo de caixa descontado (DCF) continue a ser amplamente utilizado, a sua incapacidade de contabilizar as probabilidades de insucesso do projeto pode conduzir a uma má afetação de recursos. Este estudo visa abordar esta limitação, aplicando a teoria das opções reais para avaliar o risco de abandono prematuro no contexto de um projeto de extração mineral. Neste sistema proposto, as flutuações nos custos de remediação ambiental são modeladas considerando as probabilidades cumulativas de aumentos ou diminuições de custos em cada passo de tempo. O valor simulado do projeto reflete as atividades cumulativas necessárias para o encerramento da mina, em que cada tonelada de minério extraído gera uma responsabilidade ambiental que exige reparação. Através da aplicação deste sistema, o estudo demonstra a sua eficácia na identificação de uma probabilidade crescente de encerramento de projetos ao longo do tempo. Em especial, as conclusões revelam a existência de uma data-limite crítica. Após esta data, qualquer suspensão operacional superior a um ano torna o encerramento do projeto a escolha economicamente ótima.

Este encerramento engloba todas as atividades de recuperação ambiental necessárias. Ao integrar a teoria das opções reais na avaliação do projeto, este estudo oferece uma abordagem mais abrangente para avaliar o risco de abandono prematuro do projeto em projetos de extração mineral. Através da consideração dos custos de reparação ambiental flutuantes e das probabilidades cumulativas de encerramento de projetos, fornece informações valiosas para a tomada de decisões na gestão de projetos e na afetação de recursos. A curva de desencadeamento gerada permitiu identificar o limiar de viabilidade do empreendimento. Identificando o limite para iniciar o projeto de fechamento de mineração.

Palavras-chave: Recuperação Ambiental. Fechando a Mina. Cavidades Subterrâneas Naturais. Teoria de Opções Reais. Teoria do Fluxo de Caixa Descontado.

RESUMEN

La terminación prematura de proyectos industriales, a menudo provocada por una generación insuficiente de ingresos para cubrir las responsabilidades, plantea un desafío importante en la evaluación de los proyectos. Aunque el método convencional de flujo de efectivo descontado (FCD) sigue siendo ampliamente utilizado, su incapacidad para dar cuenta de las probabilidades de fracaso del proyecto puede conducir a una mala asignación de recursos. Este estudio pretende abordar esta limitación aplicando la teoría de opciones reales para evaluar el riesgo de abandono prematuro en el contexto de un proyecto de extracción de minerales. En este sistema propuesto, las fluctuaciones en los costos de remediación ambiental se modelan considerando las probabilidades acumulativas de aumentos o disminuciones de costos en cada paso de tiempo. El valor del proyecto simulado refleja las actividades acumulativas requeridas para el cierre de la mina, donde cada tonelada de mineral extraído genera una responsabilidad ambiental que exige remediación. A través de la aplicación de este sistema, el estudio demuestra su efectividad en la identificación de una probabilidad creciente de cierre del proyecto a lo largo del tiempo. En particular, los resultados revelan la existencia de una fecha límite crítica. Más allá de esta fecha, cualquier suspensión operativa que exceda de un año hace que el cierre del proyecto sea la opción económicamente óptima. Este cierre abarca todas las actividades necesarias de restauración ambiental. Al integrar la teoría de opciones reales en la evaluación de proyectos, este estudio ofrece un enfoque más integral para evaluar el riesgo de abandono prematuro del proyecto en proyectos de extracción de minerales. Mediante la consideración de los costos fluctuantes de la remediación ambiental y las probabilidades acumulativas de cierre de proyectos, proporciona información valiosa para la toma de decisiones en la gestión de proyectos y la asignación de recursos. La curva de activación generada permitió identificar el umbral de viabilidad del negocio. Identificación del umbral para iniciar el proyecto de cierre de minería de datos.

Palabras clave: Recuperación Ambiental. Cierre de la Mina. Cavidades Subterrâneas Naturales. Teoría de Opciones Reales. Teoría del Flujo de Efectivo Descontado.

1 INTRODUCTION

Many mining ventures implicitly adopt the optimistic assumption of no catastrophic environmental failures. This translates into using the discounted cash flow (DCF) methodology under the erroneous premise of a zero probability of project failure. This essentially implies immunity to unforeseen events. However, when reality strikes with unexpected environmental issues, companies resort to depleting their reserves to sustain operations and manage the resulting ecological consequences.

While the Discounted Cash Flow (DCF) theory emphasizes Net Present Value (NPV) as a key metric for venture viability, it is crucial to recognize limitations. The conventional DCF approach employs a weighted average cost of capital (WACC) focused solely on financial risk, overlooking broader project considerations. Effective project planning necessitates continuous scenario evaluation, commencing with a comprehensive assessment of not only financial elements like costs and revenues, but also broader market dynamics and external uncertainties [1].

Based on a global survey of dam-related incidents, [2] found that mining operations were implicated in a staggering 90% of the cases examined. Notably, the study highlights a geographic trend, with a disproportionate number of occurrences concentrated in the United States, primarily involving smaller dams below 30 meters in height. This raises concerns about potential underestimation of environmental risks within the mining sector. Further underscoring this point, the authors reveal that many projects seeking metal exchange reserve certification fail to adequately consider the probability of environmental incidents. Shockingly, even those that acknowledge such risks often assign minimal reclamation costs, effectively assuming a zero probability of significant cost escalation or environmental impact.

While understanding Net Present Value (NPV) and executive compensation structures in mining companies might incentivize increased production, prioritizing output over sound operating practices can exacerbate project risk [3]. The inherent uncertainty in mining ventures has long been recognized. Pioneering efforts from the 1950s analysed various scenarios for the weighted average cost of capital (WACC) using different approaches [4]. Subsequent research built upon this foundation by

incorporating the probability of ore price fluctuations into discounted cash flow (DCF) frameworks.

[4] Paved the way for real options-based abandonment systems in mining, pioneering an approach to evaluate mine closure timing based on economic factors. Their innovative framework identified the optimal shutdown point under declining ore prices. However, this initial work had limitations. First, it made the unrealistic assumption of infinite ore reserves, neglecting the impact of resource depletion on the closure decision. Second, it assigned a zero cost to mine closure, reflecting the prevailing lack of environmental awareness at the time.

Building upon the framework for mine closure developed by Brennan in [4], Cortazar in [5] explored the potential for expansion under real options theory. While Brennan focused on economic considerations for abandoning a mine, Cortazar identified shared principles that could be adapted to an expansion model. Notably, Cortazar's model introduced arbitrage restrictions and incorporated price dynamics based on geometric Brownian motion (GBM). This enabled the simulation of fluctuating prices and costs over time. A key innovation was the inclusion of reinvestment possibilities, allowing the model to assess the feasibility of covering closure costs at any point. However, it's important to note that Brennan's work solely addressed expansion and did not account for the potential for abandonment, limiting its scope.

While [6] presents a comprehensive study encompassing the full lifecycle of a mineral venture — opening, expansion, and closure — it builds upon and significantly augments earlier models by effectively integrating a wide range of financial market complexities. However, a critical limitation lies in the model's neglect of environmental challenges, which, with their inherent stochasticity, pose a significant risk of impeding project development and viability.

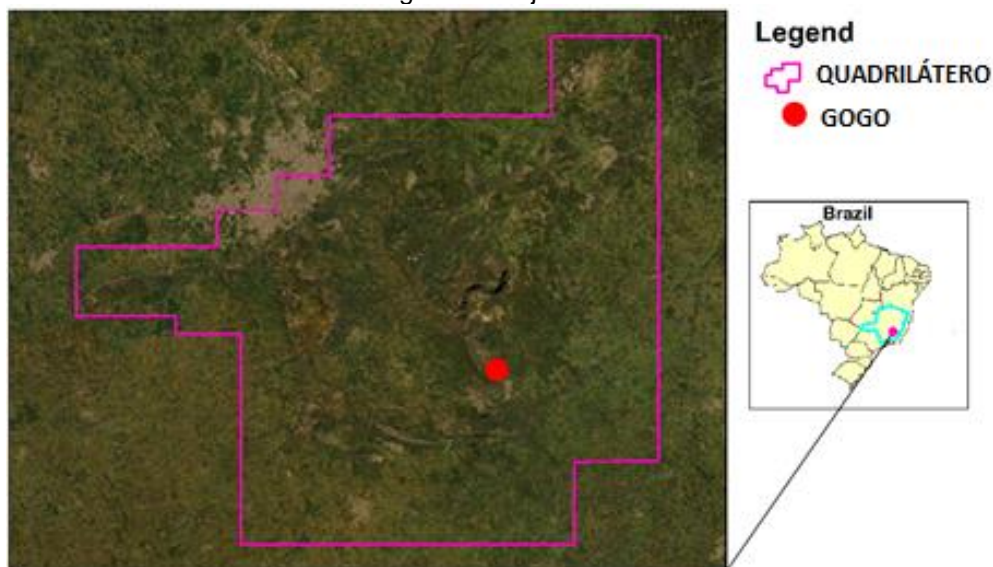
This article breaks away from the dominant trend of applying real options solely to financial market risks. It pioneers a novel approach to evaluate environmental risks in mining projects. Inspired by established methodologies for economic risk analysis, this framework quantifies environmental risk by acknowledging the irreversible nature of mine closure. By implementing this framework, the study identifies a critical threshold: any issue necessitating a cessation or suspension of activities exceeding one year triggers project closure as the most economically viable option,

encompassing all required environmental reclamation. This article employed real options theory to determine the economic threshold at which the mining venture should continue operating. The study aims to establish a methodology capable of determining the optimal arrangement to initiate the closure of the mineral venture.

2 MATERIALS AND METHODS

The case study focuses on an area within an iron formation known for hosting valuable cavities. Mining company datasets provided data on speleological exploration and cavity relevance within this area. The study area lies within the Mariana municipality (Minas Gerais State, Brazil), a region boasting several historical mining structures (18th-20th centuries) located in the south-central part of the Quadrilátero Ferrífero, which hosts significant mineral resources such as iron, gold, and manganese (Figure 2).

Figure 1. Project Area



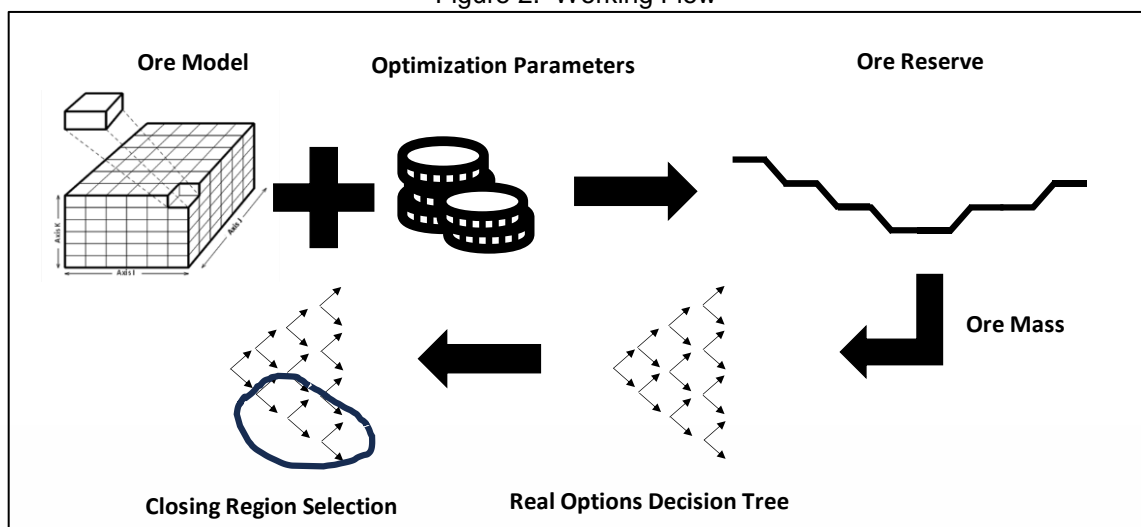
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To the development of this study a mine planning workflow, as depicted in Figure 3, followed a sequential yet interconnected approach.

1. Geological Model Construction: This initial stage utilizes data from ore sampling campaigns to build a comprehensive geological model of the deposit. This

- model captures critical aspects like orebody geometry, mineral grades, and geological features that influence mining operations.
2. **Economic Evaluation:** Concurrent with the geological model development, an economic evaluation is conducted. This involves estimating costs associated with mining, processing, and transportation, along with revenue generated by the extracted ore. Additionally, optimization parameters like production rate, minimum acceptable grade, and cut-off grades are established.
 3. **Lerchs-Grossmann Optimization:** The geological model and optimization parameters serve as inputs to the Lerchs-Grossmann algorithm. This powerful optimization tool determines the optimal pit design, maximizing the net present value (NPV) of the mining project while adhering to technical and economic constraints. The algorithm calculates the final pit limits and the total volume of ore and waste to be mined.
 4. **Decision Tree Analysis:** Understanding the project's value proposition and the anticipated volumes of extracted ore and waste is crucial for constructing a decision tree. This probabilistic tool identifies scenarios where terminating the mining operation becomes advantageous due to factors like declining profitability or exhaustion of economically viable reserves. The decision tree helps quantify the probability of encountering such scenarios and establish a clear point at which termination should be considered.

Figure 2. Working Flow



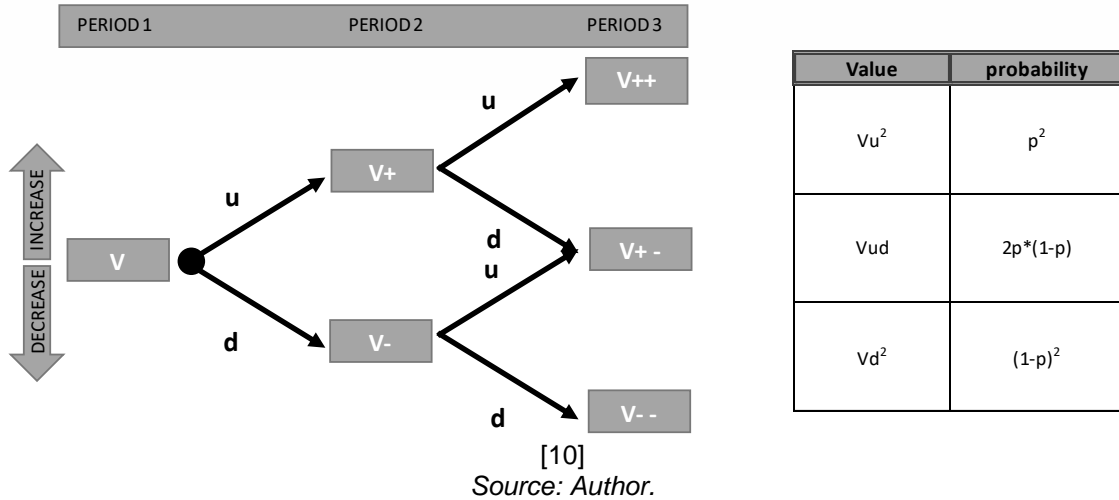
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Option theory provides a powerful tool for valuing the discretionary right, not the obligation, of a decision-maker to pursue the most advantageous outcome under uncertainty. This framework, based on the assumption of rational behaviour, allows for modelling the most likely response under various uncertain conditions. Such uncertainties are prevalent in various industries, impacting input costs, energy prices, product values, and market demand. Unlike the proposed system, traditional discounted cash flow (DCF) theory conflates investment decisions with static scenarios like waiting, contraction, or expansion, overlooking the dynamic nature of future options. Real options theory addresses this limitation by seeking to maximize the net present value of the investment opportunity. This approach involves strategically deploying real options (ROs) at opportune moments to capitalize on favourable conditions, and its value can be rigorously quantified through established financial models [8].

The decision-making system utilized for determining the closure of a mine operates on a binomial abandonment framework. At each time interval, there's the option to either continue with operations or initiate the closure process. This mirrors a behaviour akin to the sale of physical assets, anticipated by the real options methodology as a "pull" system. In this setup, the decision to closure is assessed whenever future revenues are projected to be less than the costs of maintaining the asset [9].

Figure 1 depicts the real options (RO) system's approach to quantifying temporal flexibility in decision-making. The black dot represents the initial decision point, modelled as a binary choice: increase or decrease the variable of interest. In this case, the variable under scrutiny is the cost of environmental reclamation per ton of processed ore. Initially, this variable has a value of V . Upon choosing to increase, its value changes according to Equation 1, adding the increment to the prior value. Conversely, a decrease is modelled by Equation 2, using a decrement factor. Subsequently, these updated values serve as adjustment factors (U or d) for further calculations.

Figure 3. Decision Tree



$$V_{After} = V_{previous} + u.V_{previous} \quad (1)$$

$$V_{After} = V_{previous} - d.V_{previous} \quad (2)$$

The construction of the probability tree can inadvertently introduce unrealistic economic scenarios, creating potential for arbitrage opportunities in investments. To mitigate this risk and ensure no arbitrage between branches, the values of the up and down factors (u and d) must satisfy the arbitrage-limiting inequality: $d < 1 + r < u$. This inequality explicitly incorporates the risk-free discount rate (r) to constrain the allowable range of price movements [11].

Option preparation commences with the initial phase of expanding tree scenarios. However, traversing all 2^n possible paths in n periods can quickly lead to an unwieldy computational burden. Therefore, this article leverages recombination mechanisms, ensuring that distinct paths eventually converge to similar value sequences. Crucially, the validity of the chosen recombination mechanism rests upon the condition $u \cdot V_{previous} = -d \cdot V_{previous}$, demonstrating its effectiveness in reducing computational complexity.

Building upon the model proposed by [12], this study focuses on achieving a lognormal distribution for the variable in the terminal phase (T). This objective dictates the behaviour of the up and down factors, governed by the equation $u = \exp[\sigma \cdot \sqrt{\Delta t}]$ and $d = 1/u$, where σ represents volatility and Δt is the time step. Furthermore, [13]

introduces the concept of economic depreciation into the up factor, incorporating the depreciation rate (λ) into equation 3.

$$U = e^{\sigma\sqrt{\Delta t}} \cdot (1 - \lambda \cdot \Delta t) \quad (3)$$

Within a mineral deposit, the primary depreciation mechanism is the annual extraction process, progressively depleting the remaining reserve — the core asset — across each mining stage. For the most accurate estimate, incorporating both economic and reserve depreciation is crucial. Notably, in certain derivative-related studies focusing on neutral upside risk probability (q), employing continuous-time rates rather than discrete ones is recommended. This allows for unadjusted up and down factors (u and d) to be used when evaluating cash flow, as cash flow effectively represents the venture's dividend stream [14]. Equation 4 maintains internal consistency and precludes arbitrage opportunities by incorporating a continuous-time interest rate (rc) and a risk-neutral probability for the upside scenario. This holistic approach ensures a robust and comprehensive analysis [15].

$$q = \frac{e^{(rc-\delta_c)\Delta t} - d}{u - d} \quad (4)$$

The proposed model is predicated on the assumption that the venture does not bundle spot product sales with future options. Income is solely derived from long-term contracts, justifying the use of a constant risk-neutral probability.

This novel approach leverages the classic "pull" put option to assess the economic viability of a one-year operational shutdown in the face of environmental issues. Two scenarios are compared: (1) closure with complete environmental remediation and asset divestment, and (2) continued operation with environmental mitigation. If insufficient ore remains to cover the remediation cost, the decision system dictates venture closure.

Building upon a pull selling framework, where V_t denotes the value at time t and, V_{t+1}^+ and V_{t+1}^- represents the updated values at $t+1$, and K_t signifies the exercise price

of the remaining mineral asset, the option value is calculated recursively through Equation 6 [16][17].

$$F' = \text{Max.} [\text{Perform}; \text{Wait}] \quad (5)$$

$$F'(t) = \text{Max} \{ K - V_{t_t}; [q \cdot F_{t+1}^+ + (1 - q) \cdot F_{t+1}^- - (q \cdot \delta \cdot V_{t+1}^+ + (1 - q) \cdot \delta \cdot V_{t+1}^-) \cdot \Delta t] / (1 + r) \}$$

for $t < T$ (6)

It's crucial to note that the option calculation employs a backward recursion within the framework. Equation 6 iteratively computes the up and down scenarios, progressing backwards from T towards $t=0$. Notably, as the expansion unfolds, the options switch between "exercise" and "not exercise" states — the wait option is not available in this framework. Ultimately, at the final step of the expansion ($t=0$), the option system transitions to Equation 7 for the terminal evaluation.

$$F' = \text{Max.} [\text{Perform}; 0] \quad (7)$$

Opting for operational cessation implies undertaking the complete environmental reclamation required for mine closure. This involves factoring in all accumulated mine reclamation costs up to the closure period $T-1$. Should the total reclamation cost (C_{rec}) associated with the cumulative tonnage of ore mined (T_{ac}) across all periods exceed the projected revenue, the decision system triggers project termination. Equation 8 details the calculation of the total reclamation cost [17].

$$K_t = \sum_{t=0}^{T-1} T_{ac} * C_{rec} \quad (8)$$

The growing market volatility and inherent complexity of modern mining projects are driving the adoption of real options within the metal mining industry. This powerful methodology safeguards and enhances the accuracy of expected economic returns, offering a distinct advantage compared to traditional approaches. However, it's essential to recognize the nuanced differences in applying real options for venture selection

and operational decision-making, as the technique empowers more assertive choices in specific contexts [18].

3 RESULTS AND DISCUSSION

3.1 FINANCIAL IMPACT AND MINE PLANNING

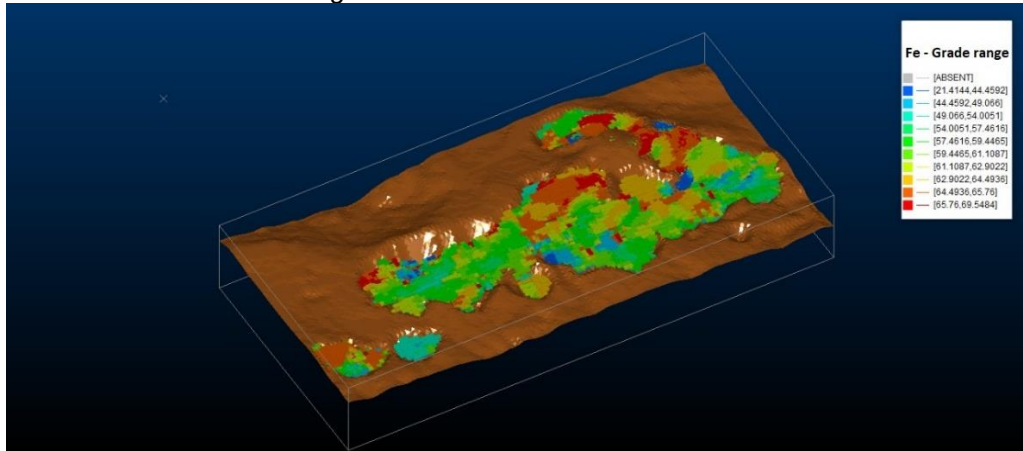
Through the studies available, the amount spent on environmental compensation was calculated using other forms of compensation, as described in IN N° 01 [19]. The financial compensation is a monetary amount determined by Brazilian law for environmental reclamation in the event of environmental damage. Finally, a block model was used for an iron ore deposit, where the mineral reserve present was calculated. The proposed economic evaluation involves the final pit design by the Lerchs & Grossmann [20] method to determine the size of the reserve and mining sequencing using the data presented in Table 1.

Table 1. Optimization Parameters

Parameter	Value
Sales Price (\$/t of Product) - All Products	70
Cost of Sale (\$/t of Product) - All Products	15
Mining Cost (\$/t of ROM) – Rich, Poor and Barren Rock	3.5
Processing Cost (\$/t of ROM) – Rich and Poor Rock	2.2
Mining Recovery (%)	100
Mining Dilution (%)	0
Annual Discount Rate (%)	10
Average Production Rate (tons/year)	60,000,000
Discount Rate (%)	10
Slope Angle (degrees)	45

Source: Author.

Figure 4. Final Pit - Iron Ore Grade

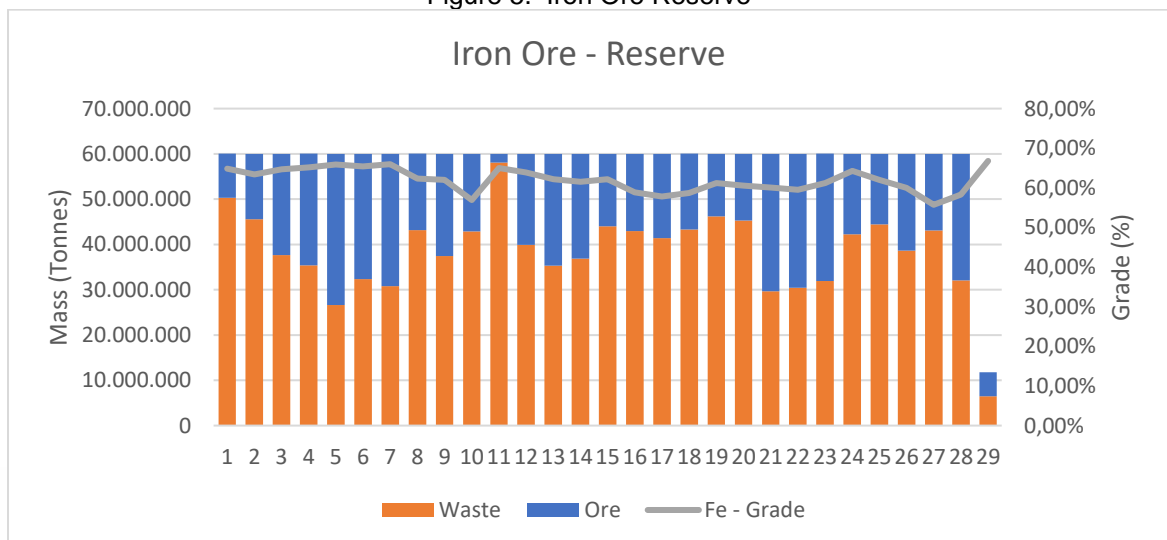


Source: Author.

3.2 PROBABILITY AND VOLATILITY ESTIMATION FOR OPTIONS SYSTEM

Utilizing the proposed options system for optimizing mining operations requires estimating the probabilities of both rising and falling ore production, along with the corresponding factors influencing each outcome. The volatility is defined as the inherent uncertainty surrounding future production levels. For this calculation, it was taken into consideration the specific context of the mining operation by deriving volatility from the standard deviation of historical increments in the total mass of ore moved.

Figure 5. Iron Ore Reserve



Source: Author.

3.3 ECONOMIC PARAMETER CALCULATION

The depreciation rate employed in the model incorporates both reserve depletion and equipment amortization. The reserve depreciation component reflects the rate at which the total reserve is mined, expressed as a percentage. To this, an adjustment factor of 0.5% of the equipment depreciation rate is added.

The upswing and downswing factors, crucial for the options analysis, are derived from Equation 3. However, the downswing factor utilizes the same equation with negative volatility to account for potential production declines. Subsequently, Equation 4 determines the upside probability, factoring in the economic depreciation incurred during the decision tree's expansion phase. A comprehensive summary of the economic parameters utilized in the model is presented in Table 2.

Table 2. Economic Parameters

Parameter	Value
Risk Free Rate (r_c) (%)	4.0
Volatility (σ)	30.7
Depreciation Rate (%)	3.9
Ascent Factor (d)	1,306
Descent Factor (u)	0,706
Ascent Probability (q) (%)	55.63
Descent Probability ($1-q$) (%)	44.37
Base Environmental Reclamation Cost (\$/t)	0.30

Source: Author

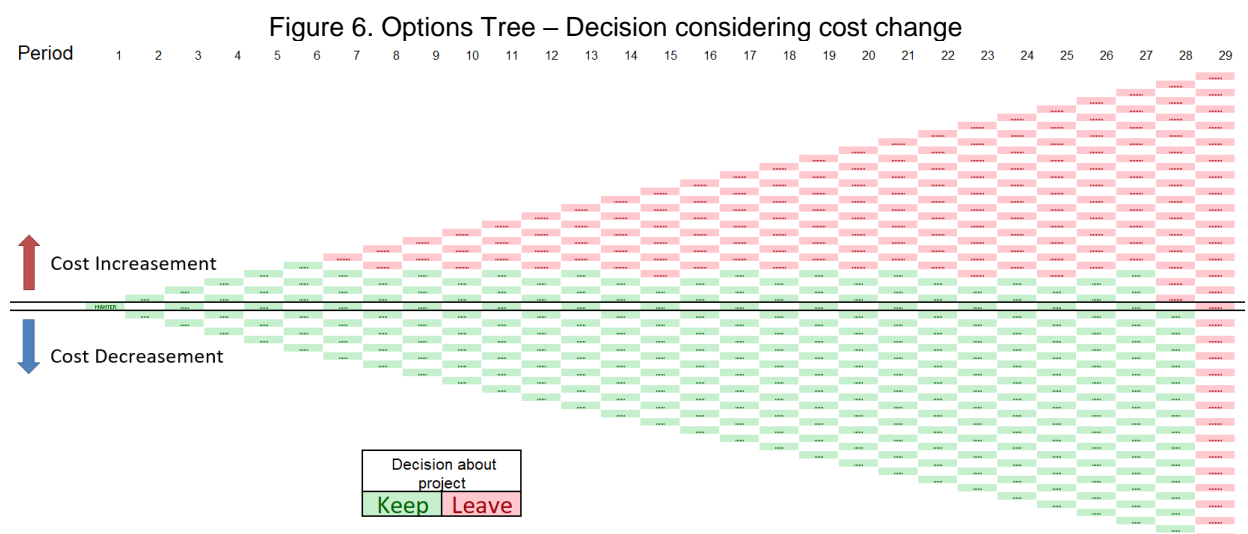
3.4 MINE SEQUENCING AND REAL OPTIONS ANALYSIS

The primary objective of the reserve sequencing process was to maximize the net present value (NPV) of the mining operation while simultaneously determining the optimal mass of ore to be sold during each period. This sequencing served as the crucial input for both cash flow projections and the real options valuation system.

Figure 6 illustrates the expanded scenario tree derived from the initial decision point depicted in Figure 1. The leftmost block represents the first period with a single probability of occurrence. Moving right, the second column of blocks introduces two

potential scenarios in the first year: an increase and a decrease in the cost of environmental reclamation. Both scenarios are assigned equal probabilities, with the green block above representing the increased cost case and the red block below representing the decreased cost case. The color coding system serves to identify optimal decision points. Green blocks indicate scenarios where continuing the mining operation remains financially viable, even despite the added constraint of environmental reclamation costs. Conversely, red blocks signify situations where the projected revenue stream is insufficient to cover the estimated environmental reclamation costs associated with the extracted ore volume.

The central black lines in Figure 6 delineate the "no change" region, where the potential increase and decrease in environmental reclamation costs exactly offset each other. In this zone, only the final period exhibits a shift towards early project termination with the presence of environmental costs. Notably, scenarios prompting potential early closure begin to emerge in period 7, albeit in the minority.



(Source: Author)

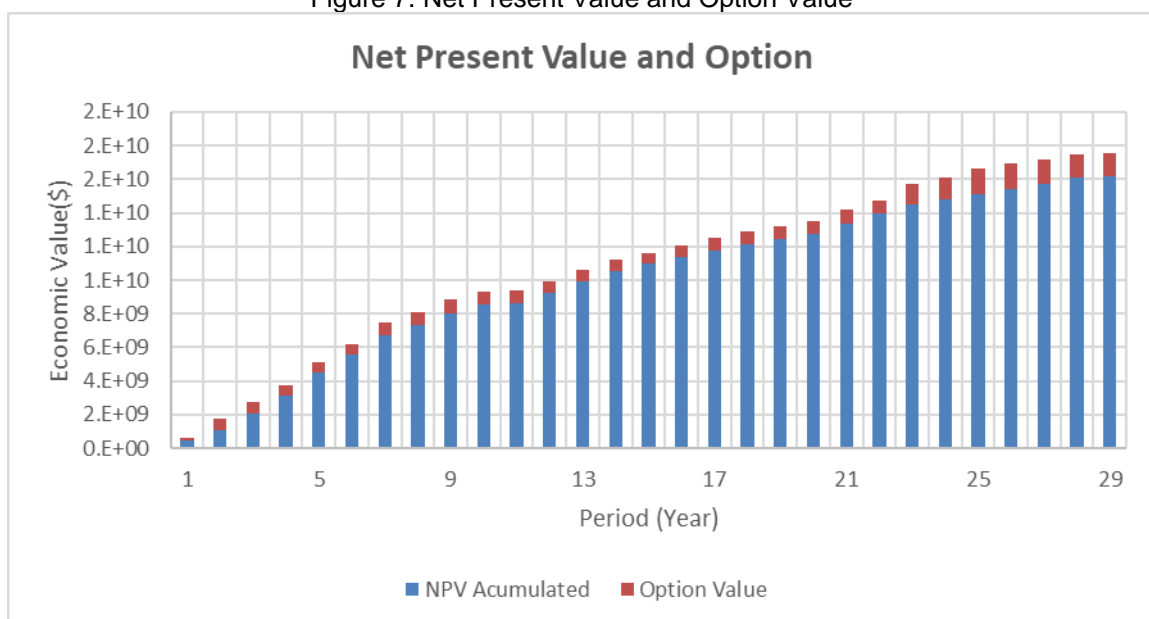
3.5 REAL OPTIONS VALUATION AND VALUE ENHANCEMENT

The application of real options theory enhances the economic analysis of the project by incorporating potential future scenarios and their associated probabilities into the financial model. The option value, representing the additional worth derived

from the flexibility to adapt to these scenarios, was determined recursively through the probability tree expansion process using Equations 5, 6, and 7.

By recursively calculating the option values at each node of the tree, one can quantify the premium added by the flexibility offered by the option. As depicted in Figure 6, the real option in this case is estimated to contribute 8.23% to the overall project value. This translates to an increase of \$1,342 million in the accumulated net present value, which reaches \$16,198 million with the option value included.

Figure 7. Net Present Value and Option Value



Source: Author.

Figure 6 reveals a critical decision boundary within each node of the option tree. This boundary, termed the cut-off point, delineates the scenarios in which project abandonment becomes financially preferable over continued operations despite incurring environmental reclamation costs.

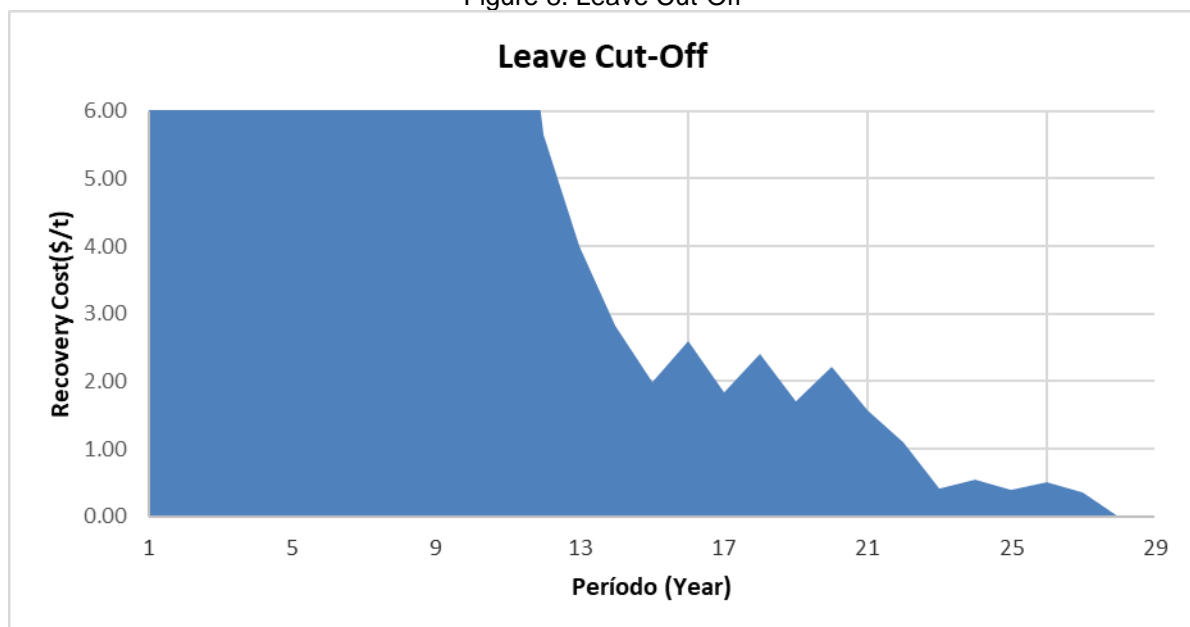
Figure 7 visually depicts these cut-off points. The shaded region denotes scenarios where project continuation is recommended, while the unshaded region above signifies those where abandonment is favoured, followed by execution of the environmental reclamation plan and its associated costs.

A notable trend emerges over time: a gradual decline in the cut-off point as the project progresses. This phenomenon stems from the increasing magnitude of environmental remediation costs that accompany greater volumes of extracted ore.

Interestingly, despite this overall downward trend, intermittent positive oscillations in the cut-off point occur during periods of heightened revenue generation within the mining plan. Periods 14 and 15 exemplify this behaviour, where a surge in processed high-grade ore triggers an upward shift in the abandonment threshold.

Consistent with the results in Fig. 6, the cut-off point approaches zero in the final period. This aligns with the financial reality that the revenue generated during the last year alone cannot adequately offset the costs of environmental reclamation and mine closure.

Figure 8. Leave Cut-Off

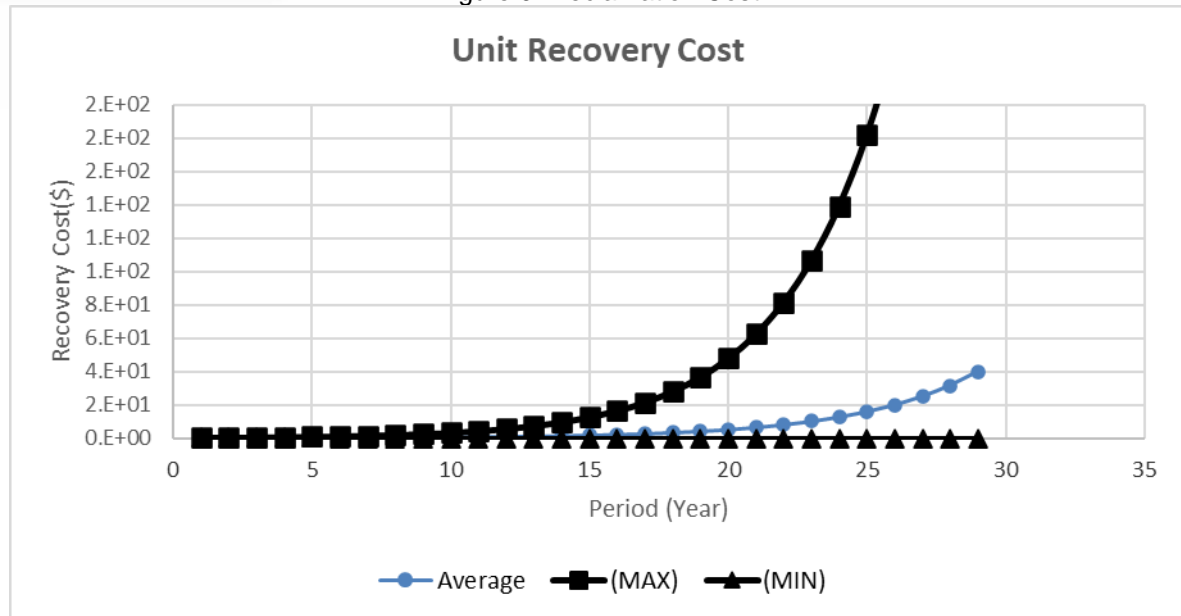


Source: Author.

Figure 8 illustrates the projected growth rate of the unit cost of environmental reclamation for three scenarios: lowest, highest, and average value. A key observation is the significant cost escalation in the extreme scenarios (low and high) towards the later periods of the mine's life. This phenomenon can be attributed to the exponential increase in environmental impact as mining progresses.

While unlikely to occur with high probability, the inclusion of extreme scenarios in the analysis is crucial for robust decision-making. As the mine approaches its end-of-life, the ratio of overburden (waste material) moved per unit of ore extracted typically increases. This translates to a substantial rise in both environmental and operational costs, potentially rendering further mining economically infeasible.

Figure 9. Reclamation Cost



Source: Author.

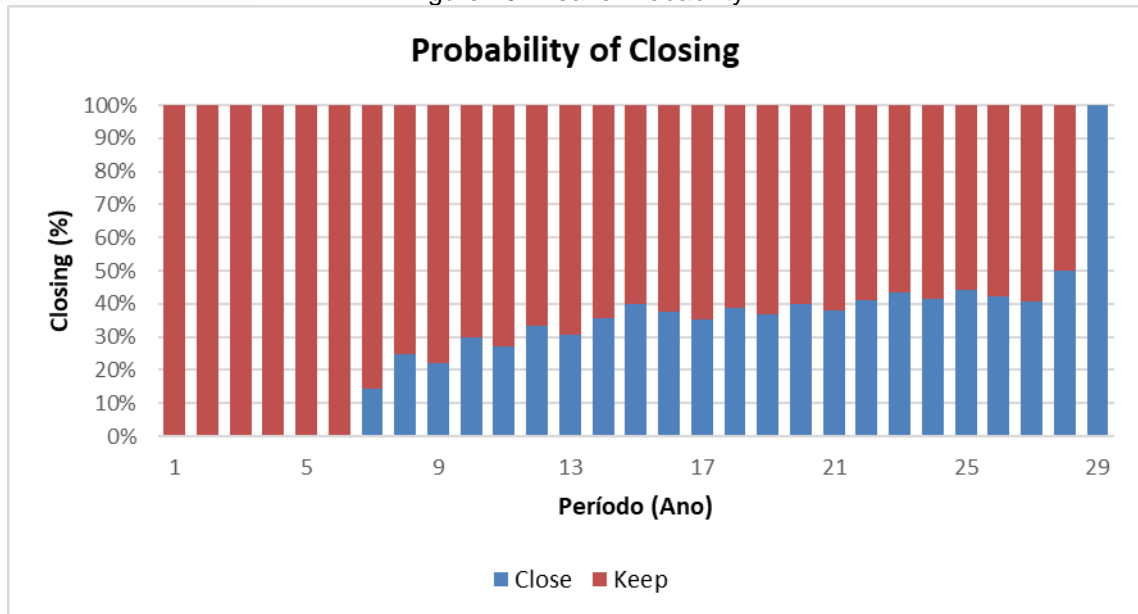
The real options framework applied in this study employs a scenario tree methodology. This allows for estimating the probability of different future outcomes arising from various uncertainties, with an initial assumption of equal probability assigned to each branch at the first decision point.

The probability of encountering a project abandonment scenario within the tree is subsequently determined by the ratio of the total number of abandonment paths to the total number of possible branches. Figure 10 visually portrays the evolution of this abandonment probability as the mining project progresses through simulated periods.

As demonstrated in the figure, period 7 marks the first appearance of potential closure scenarios in the simulated tree. Interestingly, the probability of abandonment experiences a significant upward trend until period 15, where it plateaus around 30% and remains relatively stable until the penultimate period. This trend can be attributed to accumulating environmental impacts and escalating reclamation costs as the project matures.

Finally, it is crucial to acknowledge that the last period exhibits a 100% probability of project closure regardless of the specific scenario encountered. This reflects the inherent reality that the final year alone might not generate sufficient revenue to cover environmental reclamation and closure costs for any remaining ore reserves.

Figure 10. Leave Probability



Source: Author.

4 CONCLUSIONS

The binomial expansion model, focusing solely on variations in environmental reclamation costs while holding other uncertainties constant, generated realistic scenario outcomes. The subsequent options tree analysis revealed that, under the assumption of constant costs, a deterministic planning approach would generally not lead to significant errors. This observation stems from the presence of a central region within the decision tree encompassing scenarios where continued operation remains financially viable. However, the occurrence of occasional positive fluctuations in the tree beyond year 7 indicates potential early closure scenarios. It is crucial to note that the adopted methodology assumes no ongoing environmental reclamation activities throughout the project life cycle. While reclamation efforts can be undertaken throughout the mine's life, the model considers them primarily concentrated in the mine closure phase. This study highlights the risk associated with deferring such activities, potentially jeopardizing the venture's feasibility. The cost-related risk quantification effectively identified cost thresholds surpassing which the venture becomes financially untenable, enabling proactive planning for potential early closure.

By considering a multitude of scenarios and assuming optimal economic decision-making at each juncture, the real options framework demonstrably enhances the

attainable economic value for the venture. Integrating risk into the net present value calculation revealed an 8.23% gain, which can be leveraged to mitigate unforeseen fluctuations in risks not explicitly accounted for in this study. This effectively bolsters the venture's overall robustness beyond the initial projections.

The observed trend of a decreasing cut-off point reinforces the established principle that greater adaptability exists during the early phases of a project's life cycle. Conversely, as the project approaches its end, the consequences of errors become increasingly critical, raising the probability of early closure.

While the proposed risk estimation system effectively captured cost-related uncertainties, it currently lacks a component explicitly addressing the probability of project failure. This ideally should be integrated with the operational risk component, currently modeled through production volatility. Future research could explore methodologies for incorporating and estimating such probabilities, potentially refining the volatility or fundamental risk assessment aspects of the model. Building the trigger curve allows for identifying the cost capable of rendering the mining financially unviable in advance. This enables both the venture owner and society to initiate the process of ceasing activities while there are financial resources available. This helps prevent the company from discovering insolvency when cash becomes negative. The study considered the iron ore price constant, alternating the cost in the decision tree. This is a limitation of the model, as both price and cost fluctuate over time. To enhance the system's capability, future will be developed an integration of price simulation systems into the options system may be considered. This will enable tracking the predicted fluctuation in the ore market.

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