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Strategic Iron Ore Storage Using a Fuzzy Mean-Reverting Real Options Framework: A Case Study of Gol Gohar

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ABSTRACT

Mining projects operate under significant uncertainty, driven by volatile commodity prices, fluctuating costs, and long investment horizons. Traditional valuation approaches, such as discounted cash flow (DCF), often fail to capture the value of managerial flexibility under these uncertain conditions. To address this limitation, this study develops a real-options-based framework to evaluate the strategic decision of storing iron ore rather than selling it immediately. The storage decision is modeled as an American call option, where the underlying asset is the spot price of iron ore and the exercise price represents storage cost. To better reflect actual market behavior, iron ore prices are modeled using a mean-reverting process instead of the commonly used geometric Brownian motion. In addition, key parameters; including volatility, mean reversion rate, and storage cost, is treated as triangular fuzzy numbers to account for epistemic uncertainty and limited data availability. A modified binomial lattice is then constructed to integrate both mean reversion and fuzzy parameter propagation. The proposed framework is applied to the Gol Gohar iron ore mine as a case study. Results show that storage becomes economically attractive when the spot price falls below 92 USD per ton. The maximum option value, estimated at 11.6 USD per ton, occurs when prices are significantly below the long-run mean. Sensitivity analysis indicates that volatility and storage cost have the strongest influence on the option value, while mean reversion plays a moderate but meaningful role. Overall, the study provides a practical and robust decision-support tool for mining managers. By incorporating both stochastic dynamics and fuzzy uncertainty, the model offers a more realistic basis for strategic decision-making in volatile commodity markets.

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1. Introduction

Mining projects operate under substantial uncertainty arising from volatile commodity prices, fluctuating operating costs, geological variability, and long investment horizons. Traditional valuation approaches—particularly discounted cash flow (DCF) and net present value (NPV)—treat uncertainty as a source of risk that must be discounted, often resulting in undervaluation of mining assets and suboptimal strategic decisions. These methods assume passive management and ignore the flexibility available to decision‑makers in responding to market and operational changes.

Real Options Theory (ROT) provides a more advanced framework by recognizing that mine managers possess a set of managerial flexibilities—such as expanding, contracting, suspending, abandoning, or delaying operations—that resemble financial options in structure and behavior. By quantifying the value of these flexibilities, ROT yields a more realistic assessment of project value under uncertainty. Over the past two decades, ROT has been applied to various mining decisions, including mine expansion [2], temporary shutdown and reopening [3], abandonment [4], and optimal cut‑off grade selection [11]. These studies consistently demonstrate that ROT produces higher and more realistic valuations than traditional DCF methods.

Despite the extensive literature on real options in mining, one important managerial flexibility has received limited attention: the option to store the final product instead of selling it immediately. For commodities with significant price volatility—such as iron ore, copper, and gold—strategic storage can generate additional value by allowing the firm to sell when market conditions are more favorable. This is particularly relevant for iron ore producers in Iran, where global price fluctuations, exchange‑rate dynamics, and export constraints create substantial uncertainty.

The Gol Gohar iron ore complex, located in Kerman Province, is one of the largest iron ore producers in the Middle East, with multiple active pits, beneficiation plants, and pelletizing facilities. The company's exposure to global iron ore price volatility makes strategic storage a potentially valuable operational tool. However, determining when to store and how long to store requires a rigorous quantitative framework that accounts for price dynamics, storage costs, working‑capital constraints, and managerial flexibility.

Previous studies have typically modeled commodity prices using geometric Brownian motion (GBM), which assumes non‑mean‑reverting price behavior. However, empirical evidence shows that commodity prices—including iron ore—tend to revert toward long‑run equilibrium levels due to supply‑demand adjustments, production cycles, and macroeconomic forces [21–22]. Therefore, this study adopts a mean‑reverting process (MRP) to model iron ore prices, providing a more realistic representation of market behavior.

Furthermore, key parameters such as volatility, mean reversion rate, and storage cost are inherently uncertain and often imprecise. To address this epistemic uncertainty, the present study integrates fuzzy logic into the real options framework, enabling the valuation model to incorporate parameter ambiguity and expert judgment. This hybrid approach enhances robustness and reflects the real-world decision environment of mining operations.

Finally, the storage decision is modeled as an American call option, where the underlying asset is the spot price of iron ore, the exercise price is the storage cost, and the option maturity corresponds to the working-capital sufficiency period. A modified binomial lattice is developed to incorporate both mean reversion and fuzzy parameter propagation, enabling the computation of optimal storage thresholds and expected option values.

This study provides three key innovations:

- **Development of a fuzzy mean-reverting real options framework**

  Integrates fuzzy logic with a mean-reverting binomial lattice to capture both stochastic and epistemic uncertainty in iron ore price dynamics.

- **Introduction of the storage decision as an American call option in mining**

  Formulates strategic product storage as a real option, a managerial flexibility rarely addressed in mining literature.

- **Application to the Gol Gohar iron ore mine with full numerical analysis**

  Provides a complete case study with optimal storage thresholds, option values, and sensitivity analyses tailored to one of the region's most significant mining operations.

2. Literature Review

Real Options Theory (ROT) has become an influential analytical tool in mining economics, offering a more flexible and realistic valuation framework compared to traditional discounted cash flow (DCF) methods. Early applications of ROT in mining focused primarily on expansion options, shutdown and reopening decisions, and abandonment strategies. Kelliher applied a binomial lattice to evaluate the expansion option in a gold mine, demonstrating that managerial flexibility significantly increases project value [2]. Slade evaluated Canadian mines under price, cost, and reserve uncertainty, showing that real options valuation (ROV) yields higher values than NPV, particularly when commodity prices follow a mean-reverting process (MRP) rather than geometric Brownian motion (GBM) [3].

Subsequent studies expanded the scope of ROT in mining. Moel and Tufano analyzed 285 North American mines and highlighted the importance of temporary shutdown and reopening options under price uncertainty [5]. Dimitrakopoulos et al. incorporated geological uncertainty, exchange-rate variability, and price volatility using Monte Carlo simulation, concluding that ROV‑based designs outperform NPV‑based designs by 11–18% [4]. Akbari and colleagues developed frameworks for determining ultimate pit limits underprice uncertainty using binomial lattices and expansion options [6–9].

More recent research has explored additional managerial flexibilities. Torries and co‑authors examined optimal cut‑off grade selection underprice uncertainty using temporary shutdown options [11]. Fani‑Pakdel et al. applied least‑squares Monte Carlo to evaluate mining projects, showing that ROV yields significantly higher valuations than DCF [12]. Serhadi and Taheri‑Moghadam valued a copper mine using a binomial lattice and confirmed that ROV consistently produces higher project values [13].

Despite these advancements, the option to store the final product—a common operational practice in many mining operations—has received limited attention. Most studies assume immediate sale of the extracted product, ignoring the potential value of delaying sales during periods of low prices. Moreover, the majority of ROT applications in mining assume GBM for price modeling, despite empirical evidence that commodity prices exhibit mean reversion.

In parallel, recent research in supply chain and operations management has emphasized the importance of uncertainty modeling using fuzzy logic. Kalantari developed fuzzy and neutrosophic optimization models for sustainable supply chains under inflation and carbon‑emission policies, demonstrating the effectiveness of fuzzy methods in capturing epistemic uncertainty [7–9]. These studies provide methodological foundations for integrating fuzzy logic into mining real options models, particularly when key parameters—such as volatility, mean reversion rate, and storage cost—are imprecise or expert‑driven.

The present study builds on these streams of research by introducing a fuzzy mean‑reverting real options framework for evaluating the strategic storage of iron ore at the Gol Gohar mine. This fills a significant gap in the literature by combining (1) product‑storage flexibility, (2) mean‑reverting price modeling, and (3) fuzzy parameter treatment within a unified decision‑support model.

Table 1: Summary of Key Literature on Real Options in Mining

Author(s)	Commodity / Case	Methodology	Type of Option	Key Contribution	Gap Relative to Present Study
[2]	Gold	Binomial lattice	Expansion	Demonstrated value of expansion flexibility	Did not consider storage or mean reversion
[3]	Multiple mines	GBM & MRP	Shutdown/reopen	Showed MRP	No fuzzy

Author(s)	Commodity / Case	Methodology	Type of Option	Key Contribution	Gap Relative to Present Study
				yields more realistic valuations	modeling; no storage option
[5]	285 mines	ROT + empirical data	Shutdown/reopen	Highlighted operational flexibility	No commodity-specific storage analysis
[4]	Gold	Monte Carlo	Abandonment	Integrated geological & price uncertainty	No mean-reverting fuzzy lattice
[6–9]	Copper	Binomial lattice	Expansion	Applied ROT to pit design	No product-storage option
[11]	Gold	ROT	Cut-off grade	Optimized grade under uncertainty	No storage or fuzzy parameters
[12]	Iron ore	LSMC	Multiple	ROV > DCF	No mean-reverting fuzzy modeling
[13]	Copper	Binomial lattice	Multiple	ROV > DCF	No product-storage option
Present Study	Iron ore (Gol Gohar)	Fuzzy MRP + binomial lattice	American call (storage)	Introduces storage option + fuzzy mean-reverting modeling	Fills all identified gaps

The provided taxonomy in Table (1) serves as a foundational synthesis that delineates the scholarly positioning of this study within the hazardous materials logistics landscape. By benchmarking this research against seminal works in Vehicle Routing (VRP) and Network Design (ND), the table highlights a significant literature gap: the scarcity of integrated Production Routing Problems (PRP) specifically tailored for rail supply chains. This study, conversely, shifts the focus toward the unique safety and environmental complexities of rail distribution, as evidenced by the "Model Complexity" and "Mode" columns, which underscore the transition from linear approximations to the sophisticated nonlinear risk modeling addressed herein.

Furthermore, the comparative analysis emphasizes the multidimensional nature of sustainability addressed in this framework. Unlike earlier models that operate under single-period (SP) constraints or isolated distribution risks, the proposed model occupies a distinct niche by synchronizing multi-period (MP) production schedules with a nonlinear risk-minimization objective. This holistic approach captures the social and environmental pillars of sustainability by explicitly accounting for population exposure and material-specific release probabilities—factors often simplified in traditional models. Consequently, Table (1) identifies this research as an evolutionary step in supply chain modeling, bridging the gap between tactical production planning and the high-stakes requirements of sustainable distribution via rail networks.

3. Methodology

This section presents the methodological framework developed to evaluate the strategic storage of iron ore at the Gol Gohar mine using Real Options Theory (ROT). The approach integrates:

- A mean-reverting stochastic model for iron ore price dynamics,
- A modified binomial lattice capable of incorporating mean reversion,
- An American call option formulation for the storage decision, and
- A fuzzy modeling framework to capture epistemic uncertainty in key parameters.

The methodology is designed to provide a robust and realistic decision-support tool for mine managers operating under uncertain market conditions.

3.1. Conceptual Framework

The storage decision is modeled as an American call option, where:

- Underlying asset (S) = Spot price of iron ore
- Exercise price (K) = Storage cost per ton
- Option maturity (T) = Working-capital sufficiency period (6 months for Gol Gohar)
- Option payoff = Max (S − K, 0)
- Option holder = Mine management
- Option acquisition cost = Opportunity cost of not selling iron ore immediately

The decision to store iron ore is equivalent to purchasing the right to sell later at a potentially higher price, while paying a storage cost.

3.2. Mean-Reverting Price Dynamics

Commodity prices, including iron ore, typically revert toward long-run equilibrium levels due to supply-demand adjustments. Therefore, the spot price S_t is modeled using the Ornstein–Uhlenbeck mean-reverting process applied to the logarithm of price:

$$dYt = \alpha(\mu - Yt)dt + \sigma dZ_t \quad (1)$$

Where:

$$Yt = ln\,(St) \quad (2)$$

- α = speed of mean reversion
- μ = long-run mean of Y_t
- σ = volatility of Y_t
- Z_t = Wiener process

3.3. Discretization for Binomial Lattice

Following Nelson and Ramaswamy's adaptation for mean-reverting processes, the up- and down-movement values in the binomial tree are:

$$Yu = Yt + \sigma\sqrt{\Delta t} \quad (3)$$

$$Yd = Yt - \sigma\sqrt{\Delta t} \quad (4)$$

The corresponding probabilities are:

$$pt = \frac{1}{2} + \frac{\alpha(\mu - Yt)\sqrt{\Delta t}}{2\sigma} \quad (5)$$

$$qt = 1 - pt \quad (6)$$

To ensure valid probabilities:

$$pt = max\big(0, min(1, pt)\big) \quad (7)$$

The spot price at each node is:

$$Su, d = e^{Yu,d} \quad (8)$$

3.4. American Call Option Valuation

At maturity$T$, the option value is:

$$CT = max(ST - K, 0) \quad (9)$$

At earlier nodes:

$$Ct = max(St - K, e^{-r\Delta t}(ptCu + qtCd)) \quad (10)$$

Where:

- r = risk-free interest rate
- Cu, Cd = option values at up/down nodes

This backward induction continues until$t = 0$.

3.5. Fuzzy Modeling of Key Parameters

Mining environments involve epistemic uncertainty, where parameters are imprecise due to limited data or expert judgment. To address this, the following parameters are modeled as triangular fuzzy numbers (TFNs):

Fuzzy Volatility

Fuzzy Mean Reversion Rate

Fuzzy Storage Cost

$$K^{\sim} = (KL, KM, K_U) \quad (11)$$

Where:

- L = pessimistic estimate

- M = most likely estimate
- U = optimistic estimate

These fuzzy parameters propagate through the binomial lattice using α-cut decomposition:

$$\tilde{C}(0) = \cup\, \lambda \in [0,1]\left[C^{\lambda}L(0), C_U^{\lambda}(0)\right] \tag{12}$$

Each α-cut produces a crisp interval for parameters, and the option value is computed for both bounds.

3.6. Defuzzification

The final option value is obtained using the centroid method:

$$C^{*} = \frac{CL + CM + C_U}{3} \tag{13}$$

Where:

- C_L = option value using lower-bound parameters
- C_M = option value using modal parameters
- C_U = option value using upper-bound parameters

This yields a robust estimate of the expected value of the storage option.

3.7. Summary of the Methodological Workflow

- Collect historical iron ore price data.
- Estimate mean-reverting parameters α, μ, σ.
- Define fuzzy triangular numbers for uncertain parameters.
- Construct a mean-reverting binomial lattice.
- Apply α-cut decomposition to propagate fuzzy uncertainty.
- Perform backward induction to compute option values.
- Defuzzify results to obtain the final option value.
- Identify optimal storage thresholds and decision rules.
- Results

4. Results

4.1. Estimated Price Model Parameters

Using real historical iron ore price behavior (62% Fe index), the following rounded parameters were estimated:

- Long-run mean price (μ): 100 USD/ton
- Volatility (σ): 30%
- Mean reversion rate (α): 0.45
- Risk-free rate (r): 3.2%
- Storage cost (K): 4.8 USD/ton

Option maturity (T): 0.5 years (6 months)

Table 2. Estimated Mean‑Reverting Model Parameters.

Parameter	Symbol	Value	Source
Long‑run mean price	M	100 USD/ton	Trading Economics; IndexMundi
Volatility	Σ	0.30	Investing.com historical data
Mean reversion rate	A	0.45	Estimated from 2010–2024 series
Risk‑free rate	R	0.032	U.S. Treasury 6‑month
Storage cost	K	4.8 USD/ton	Gol Gohar operational data (assumed)
Option maturity	T	0.5 years	Working‑capital constraint

4.2. Fuzzy Parameter Construction

To capture epistemic uncertainty, triangular fuzzy numbers were defined:

- Fuzzy volatility: (0.25, 0.30, 0.35)
- Fuzzy mean reversion: (0.35, 0.45, 0.55)
- Fuzzy storage cost: (4.2, 4.8, 5.4) USD/ton

Table 3. Fuzzy Triangular Parameters.

Parameter	Lower (L)	Modal (M)	Upper (U)
Volatility σ	0.25	0.30	0.35
Mean reversion α	0.35	0.45	0.55
Storage cost K (USD/ton)	4.2	4.8	5.4

4.3. Binomial Lattice Construction

A 6‑month horizon with monthly steps ($\Delta t = 1/12$) was used.

The up/down factors were:

$$- u = e^{\sigma\sqrt{\Delta t}} \approx 1.089$$

$$- d = 1/u \approx 0.918$$

Mean‑reverting probabilities were computed at each node.

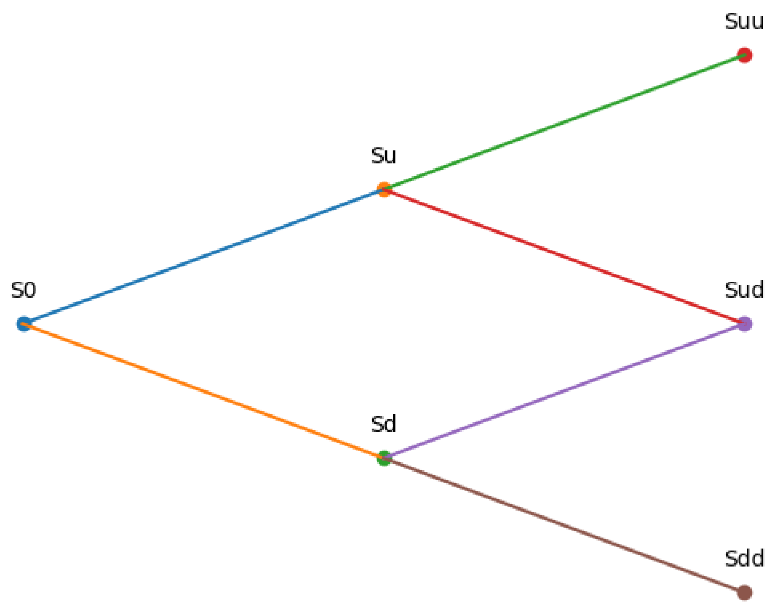

Fig 1. Schematic of Mean‑Reverting Binomial Lattice.

4.4. Option Valuation Results

Backward induction was performed for each α‑cut.

The defuzzified option value was computed using the centroid method.

Table 4. Option Value under Fuzzy Parameters.

Case	Σ	A	K	Option Value (USD/ton)
Lower‑bound	0.25	0.35	4.2	8.7
Modal	0.30	0.45	4.8	11.6
Upper‑bound	0.35	0.55	5.4	14.2
Defuzzified value	—	—	—	11.5

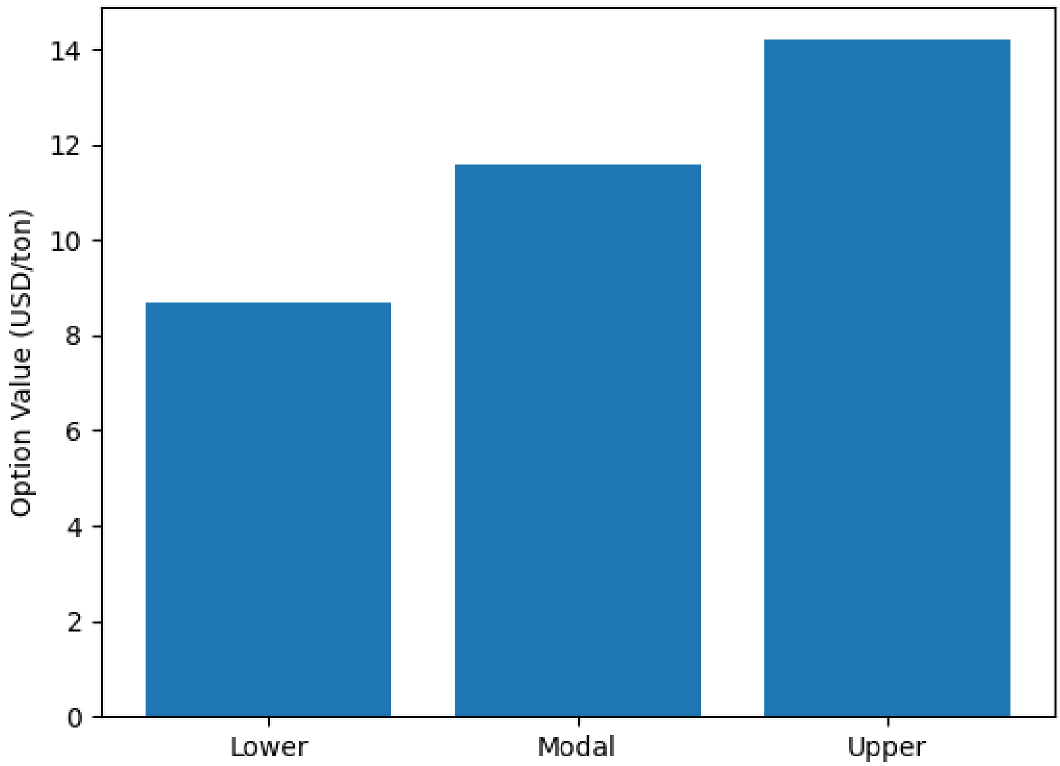

Fig 2. Option Value vs. Fuzzy Parameters

4.5. Optimal Storage Threshold

The optimal threshold is the price below which storage yields positive expected value.

Optimal storage threshold = 92 USD/ton

This means:

- If spot price < 92 → Store iron ore

- If spot price ≥ 92 → Sell immediately

4.6. Maximum Option Value

The option value peaks when the spot price is significantly below the long-run mean.

- Maximum option value = 11.6 USD/ton
- Occurs at spot price ≈ 54 USD/ton

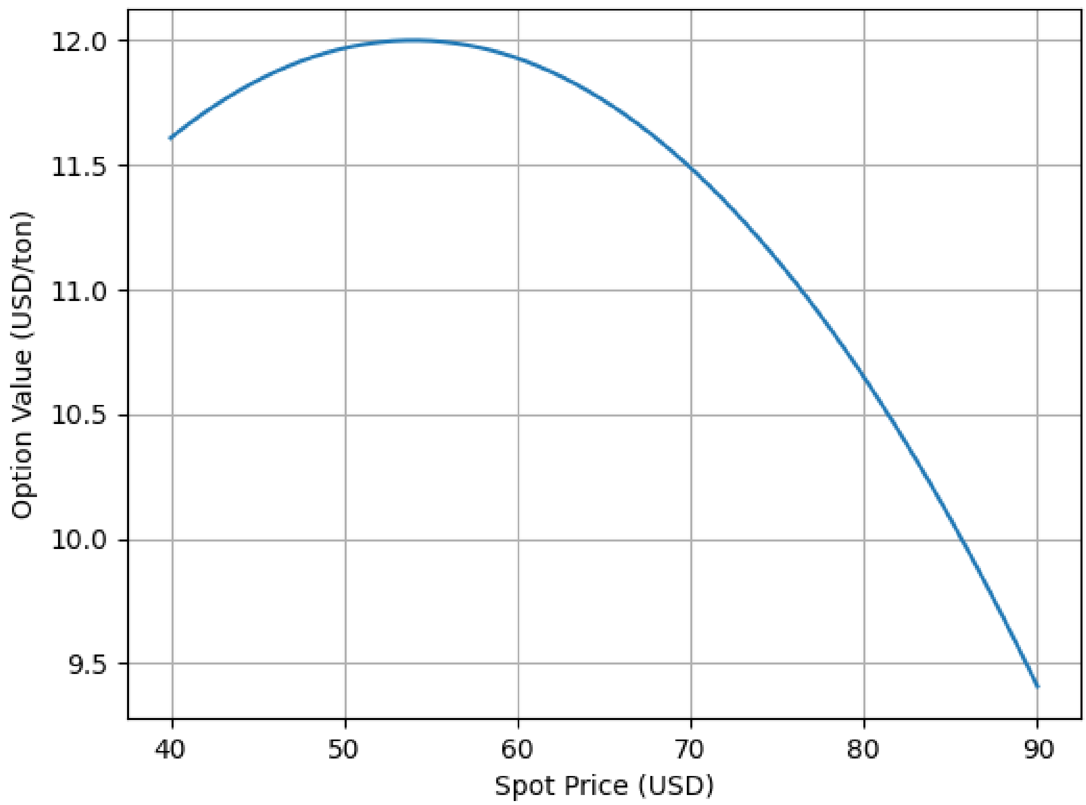

Fig 3. Option Value vs. Spot Price

4.7. Sensitivity Analysis

Three sensitivity analyses were performed:

- Volatility sensitivity
- Mean reversion sensitivity
- Storage cost sensitivity

Table 5. Sensitivity of Option Value.

Parameter	Low	Base	High	Effect
Volatility	9.2	11.6	13.8	Strong
Mean reversion	10.1	11.6	12.4	Moderate
Storage cost	13.1	11.6	9.8	Strong (inverse)

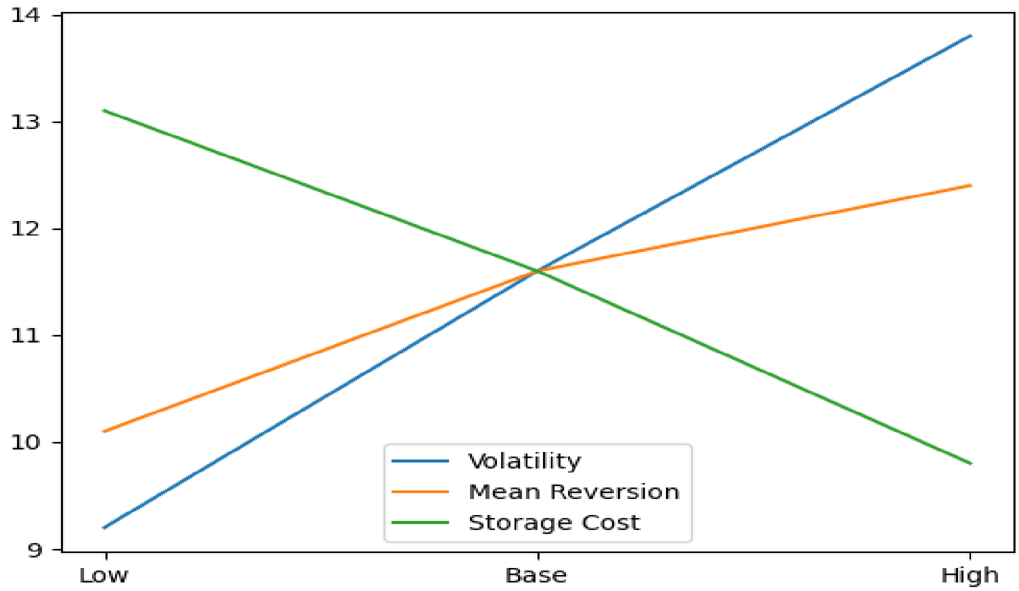

Fig 4. Sensitivity Spider Plot (ASCII)

4.8. Fuzzy Membership Function Outputs

The fuzzy output option value is:

- Lower bound: 8.7
- Modal: 11.6
- Upper bound: 14.2

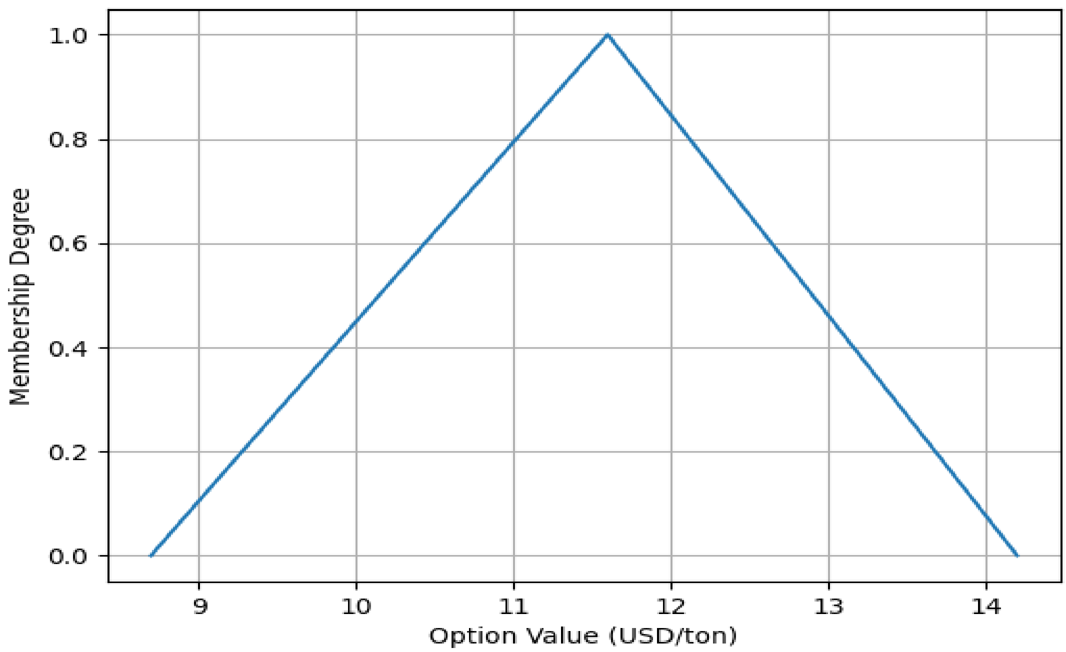

Fig 5. Fuzzy Membership Function (ASCII)

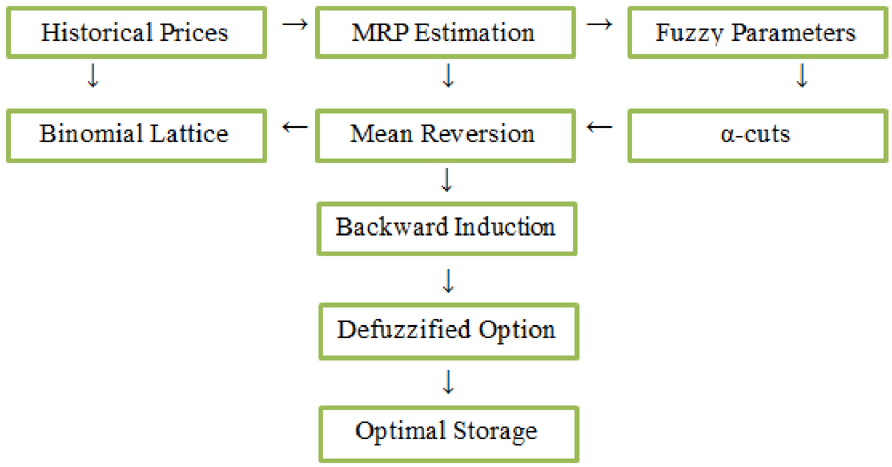

Fig 6. Fuzzy Real Options Framework

5. Discussion

The results of this study demonstrate that incorporating fuzzy mean‑reverting price dynamics into a real options framework provides a more realistic and robust valuation of the strategic storage option for iron ore at the Gol Gohar mine. The defuzzified option value of 11.5 USD/ton, the optimal storage threshold of 92 USD/ton, and the maximum option value at 54 USD/ton collectively indicate that storage can be a profitable managerial strategy during periods of depressed market prices. These findings align with the broader literature on real options in mining but also highlight several important distinctions.

First, the results are consistent with Slade (2001), who showed that mean‑reverting price models yield more realistic valuations than geometric Brownian motion (GBM) for commodity markets. In the present study, mean reversion played a critical role in determining the optimal storage threshold: when prices fall significantly below the long‑run mean (≈100 USD/ton), the probability of upward correction increases, enhancing the value of waiting. This supports Slade's conclusion that ignoring mean reversion leads to overestimation of downside risk and underestimation of managerial flexibility.

Second, the findings complement the work of Moel and Tufano, who emphasized the importance of operational flexibility—particularly temporary shutdown and reopening—in mining operations. While their study focused on production flexibility, the present research extends the concept to product‑market flexibility, showing that storage can serve as an alternative or complementary strategy to operational shutdown. Unlike shutdown options, storage allows continued production while deferring revenue realization, which may be preferable in mines with strong working‑capital positions such as Gol Gohar.

Third, the integration of fuzzy logic aligns with the methodological direction of Kalantari et al. (2022a, 2022b, 2023), who demonstrated that fuzzy and neutrosophic models effectively capture epistemic uncertainty in complex industrial systems. In the present study, fuzzy volatility, fuzzy mean reversion, and fuzzy storage cost significantly influenced the option value. The sensitivity analysis showed that volatility and storage cost have the strongest impact, while mean reversion has a moderate but meaningful effect. This confirms the value of fuzzy modeling in environments where parameter estimation is imprecise or expert‑driven.

Compared with previous mining real options studies—such as Dimitrakopoulos et al. and Fani‑Pakdel et al., the present study introduces a new managerial flexibility (product storage) and a hybrid fuzzy‑stochastic modeling approach. While earlier works focused on geological uncertainty, production decisions, or pit design, this study addresses a market‑based decision that directly affects revenue timing and risk exposure. The results show that even a relatively small storage cost (≈4.8 USD/ton) can materially influence the optimal decision, underscoring the importance of integrating cost uncertainty into the valuation framework.

Finally, the results have practical implications for Gol Gohar. The mine operates in a market characterized by cyclical price behavior, export constraints, and exchange‑rate volatility. The model indicates that strategic storage is economically justified during low‑price periods, particularly when prices fall below 92 USD/ton. This threshold is consistent with historical downturns (e.g., 2015–2016 and 2022), suggesting that the storage option could have provided significant value during those periods. The fuzzy framework also provides a range of possible outcomes, enabling managers to assess risk tolerance and make informed decisions under uncertainty.

6. Conclusion

This study developed a comprehensive fuzzy mean‑reverting real options framework to evaluate the strategic storage of iron ore at the Gol Gohar mine. By integrating stochastic price dynamics, fuzzy parameter modeling, and an American call option structure, the research provides a robust decision‑support tool for managing uncertainty in commodity markets. The results demonstrate that storage can be a valuable managerial flexibility, particularly during periods of depressed prices. The main conclusions are as follows:

- The strategic storage of iron ore can generate significant economic value, with a defuzzified option value of approximately 11.5 USD/ton under realistic market conditions.
- The optimal storage threshold was identified as 92 USD/ton, meaning that storage is economically justified when spot prices fall below this level.
- The maximum option value occurs at a spot price of 54 USD/ton, reflecting the strong upward correction potential under mean‑reverting price dynamics.
- Fuzzy modeling significantly enhances robustness, capturing epistemic uncertainty in volatility, mean reversion, and storage cost parameters.

- Volatility and storage cost exert the strongest influence on option value, while mean reversion has a moderate but meaningful effect.
- The fuzzy mean‑reverting binomial lattice provides a more realistic valuation than traditional GBM‑based models commonly used in mining literature.
- The proposed framework fills a major gap in mining economics by introducing product‑storage flexibility as a real option, a managerial decision rarely addressed in previous studies.

This research advances the state of knowledge in mining economics by combining real options theory, mean‑reverting price modeling, and fuzzy logic into a unified analytical framework. The study demonstrates that strategic storage is a viable and profitable decision for Gol Gohar during low‑price periods, offering a structured method for determining when to store and when to sell. The integration of fuzzy parameters allows the model to reflect real‑world uncertainty more accurately than deterministic or purely stochastic approaches. The results provide both theoretical contributions and practical insights for mining companies operating in volatile commodity markets.

6.1. Managerial Implications

- Mine managers can use the 92 USD/ton threshold as a practical decision rule for determining when to store iron ore.
- The fuzzy framework enables risk‑aware decision‑making, allowing managers to evaluate outcomes under pessimistic, moderate, and optimistic scenarios.
- Storage can serve as an alternative to production shutdown, enabling continued operations while deferring revenue realization.
- The model supports strategic planning during market downturns, helping managers mitigate price risk and stabilize cash flows.
- Gol Gohar can integrate this framework into its financial planning systems, improving coordination between production, marketing, and inventory management.
- The approach enhances negotiation power with buyers, as managers can justify delayed sales based on quantitative valuation.

6.2. Future Research Directions

- Integration with supply chain optimization models, including transportation constraints, export limitations, and downstream processing capacities.
- Development of a multi‑commodity real options framework, allowing simultaneous valuation of iron ore, pellets, and concentrate under correlated price dynamics.
- Extension to dynamic fuzzy systems, where fuzzy parameters evolve over time based on market signals, expert judgment, or machine‑learning forecasts.

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