The Option to (Re)develop or Abandon a Mature Depreciating Oil Field

Maher Al-Sharea

Institute of Geo-Energy, Heriot Watt University, Edinburgh, Scotland, UK

March 2024

Abstract

Towards the end of the life of mature fields, the decline in production leads to diminishing cash flows. At this stage, the operator faces the crucial decision of either continuing, abandoning, or reaching for remaining, but harder-to-access reserves. The timing of this decision has economic consequences, particularly with uncertain prices and technical challenges.

The optimal decision of redevelopment or abandonment depends on the level of prices and the chance of success in accessing added reserves. We use an integrated real options framework through an illustrative example to discuss solutions and sensitivities to this multi-dimensional problem.

Introduction

Approximately 70% of the world's oil-producible fields are presently categorized as mature fields and the number of such fields has been steadily increasing (O'Brien et al., 2016). Mature fields are defined to be those that have reached the plateau production phase, the decline phase may have started, and the fields are reaching the end of their economic life. In a field development plan, once the initial number of wells applicable to the field is reached, field redevelopment practices such as infill drilling and re-entries are taken into consideration to maximize the project value. Infill drilling has been widely adopted as an industry standard for several decades, primarily due to the non-homogeneous characteristics observed in most reservoirs worldwide. In this research, we address the value of flexibility of infill drilling in mature field development, with a specific focus on underbalanced coiled tubing drilling (UBCTD) as a promising technology for re-entry drilling in depleted mature fields.

When the cash flow of a mature field declines, field operators are confronted with a strategic decision—to either persist with the declining value, embark on the redevelopment of the field, or opt for permanent abandonment. The multifaceted uncertainties, including declining production, geological limitations, and oil price fluctuations, contribute to the complexity of the decision-making process. For a development option to be economically viable, its future value must surpass the associated costs. Oil price fluctuations have a considerable effect on these decisions, particularly for marginal fields.

The challenges associated with accessing remaining reserves in a reservoir evolve over time as the reservoir matures. This transformation is primarily influenced by geological factors, including depletion. Underbalanced coiled tubing drilling UBCTD is a drilling technology that has proven to be well-suited for depleted reservoirs.

Additionally, it offers cost savings by replacing the conventional rig with a small, coiled tubing unit (Doremus & Dowell, 1995). The literature demonstrates the successful implementation of this technology for re-entry drilling in depleted mature fields (Iadc et al., 2013) and (Krueger & Pridat, 2016). However, this drilling method carries inherent risks, including the potential for formation collapse, representing a worst-case scenario where the target may not be reached, and the well cost is lost.

The literature extensively discusses the technical success of this technology and highlights numerous cases where cost savings compared to conventional drilling are indicated such as Burke et al., (2014), Iadc et al., (2013), and Krueger & Pridat, (2016). However, the existing literature does not provide a general cost-saving value that can be used for a feasibility study. We found that CTD yields an average cost savings of 34% compared to conventional rigs. Additionally, the literature reveals that Underbalanced Coiled Tubing Drilling (UBCTD) improves productivity and adds incremental recovery to mature fields (Johnson et al., 2008). Underbalanced drilling enhances productivity with a general average productivity index factor (PIF) of 1.84, falling within the range of 1.07 to 3.16. Additionally, it contributes to additional recovery with an average of 17%, within the range of 3% to 50% (Al-Sharea, 2024). However, a noticeable gap exists in the literature regarding the optimal timing for its implementation to maximize the value of the project.

The field of real options has endeavoured to deal with similar issues (Lund, 2000), (Smith, 2005),and (Jafarizadeh & Bratvold., 2019). However, many model formulations tend to oversimplify the technical options. Conversely, some studies are sophisticated to be understood and implemented by operators in the oil and gas industry. Complexities arising from decisions made at the beginning of a field's lifetime or employing complex computational approaches to problem-solving often prove impractical for oil and gas practitioners. We pay more attention to the technical and geological uncertainties, while consistently managing price uncertainty. We provide a simplified but informative decision framework to solve the complex decision.

We found that the application of this drilling method is restricted by both geological and economic factors, within a limited time frame. Initiating this option during periods of low oil prices diminishes the project's value. Conversely, delaying it for more favourable economic conditions could result in the expiration of this option due to geological constraints. However, the discounted value of abandonment costs contributes to delaying abandonment by providing added value. The chance of success, drilling cost, and expected recoverable reserves associated with this drilling technology are decisive factors. We rely on the literature to calculate a cost-saving factor for this method compared to the well-known traditional drilling method. Additionally, we determine the average barrels that can be added by utilizing this technology and the abandonment cost of onshore wells. Then we employ a flexible Markov chain process as mentioned by Jafarizadeh & Bratvold., (2019), assuming that the optimal decision relies on the stochastic mean-reverting nature of prices, represented using a discrete version of Hahn & Dyer, (2008). We use the mentioned concept in our binomial lattice for Markov decision chain. The algorithm is implemented using Excel Visual Basic for Applications (VBA). Additionally, we conduct a sensitivity analysis of the key parameters. This model introduces an informed simplicity to address technical, geological, and economic factors within a clear and accessible framework. Additionally, the model enables user to easily change the inputs.

This paper is structured as follows: we provide a brief review of the challenges in the development of mature oil fields, and the probability of successfully accessing the remaining reserves in depleted reservoirs. Additionally, a general decision framework is constructed. We then outline oil price models and the discrete processes involved in them. After that we introduce the Markov chain approach and its implementation in our case. Finally, we present the discussion, conclusion, and suggestions for further research.

Challenges in the Development of Mature Oil Fields

Hydrocarbons trapped in depleted, heterogeneous, fractured, and heavily faulted mature reservoirs were commonly regarded as non-commercial or challenging resources, primarily because of the reservoir's complex nature and the difficulties posed by depletion (Johnson et al., 2008). These challenges encompass accessibility and economic viability. When production declines, the field operators decide whether to pursue re-entry drilling if the expected future value of this option surpasses the value of continuing with the current declining production, or alternatively, they abandon the field if the future value is less promising. When a re-entry decision is made, the associated abandonment costs are deferred to a later time, generating additional value through the discounting of these costs. In the oil industry, it is common practice to disregard oil price flexibility and solely rely on technical factors when determining the optimal timing for infill drilling. However, fluctuations in oil prices have a significant impact on determining the optimal time to take this action as shown in Figure (1).

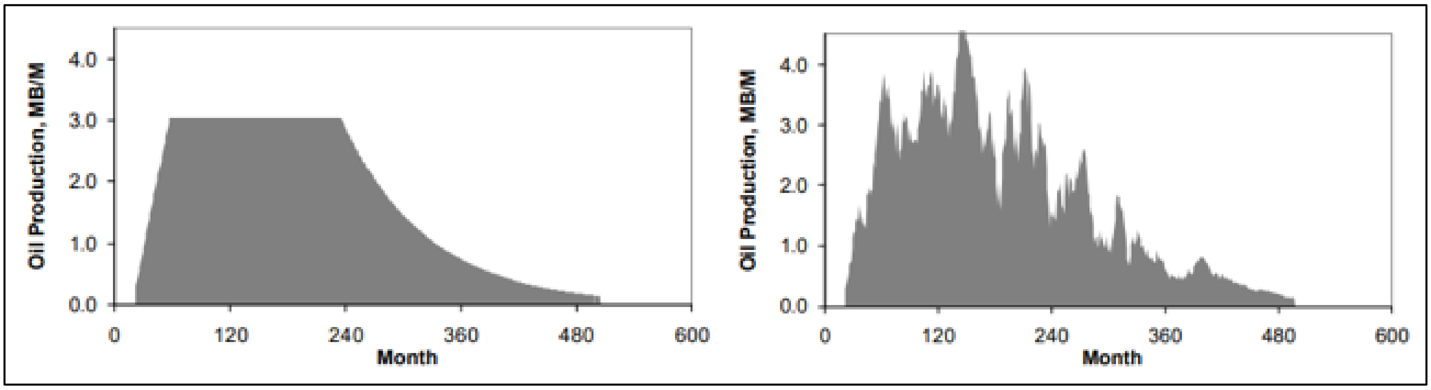


Figure 1:Production profile with no correlation with oil prices (left), production profile correlated with oil prices (right) (Begg et al., 2002).

The window for infill drilling opens once the production decline is confirmed and closes either due to economic feasibility or geological difficulties (accessibility), depending on whichever comes first as shown in Figure (2). From the moment this option becomes valid until its expiration, there is ample time to consider the value of flexibility. We address these inquiries: Does the value of this option surpass the associated costs? When is the optimal time to drill re-entries within the decision window and what is the value of flexibility?

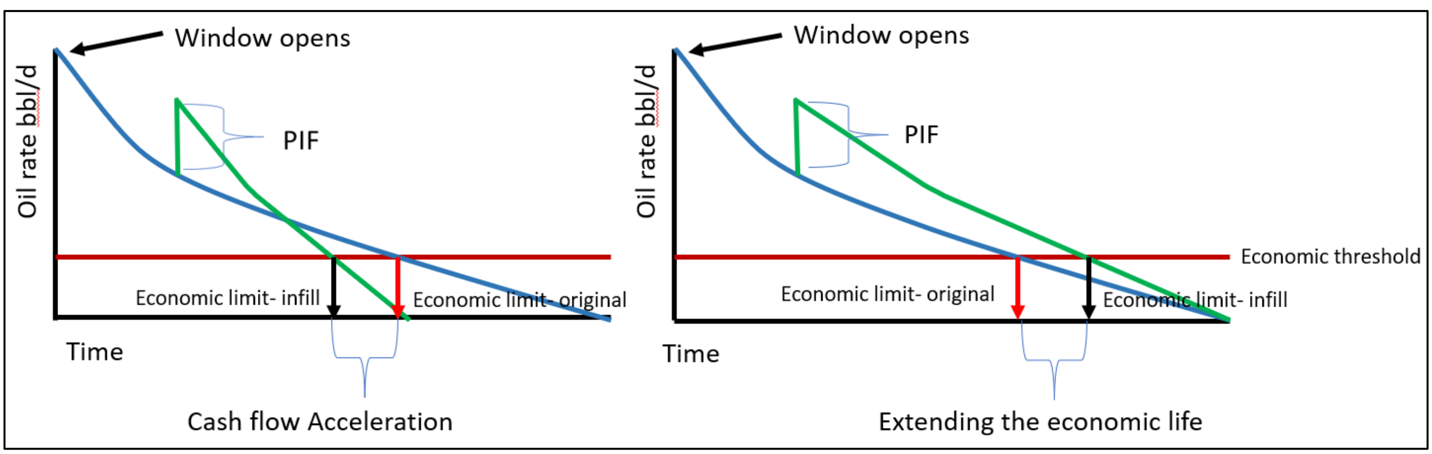


Figure 2: illustrates the economic feasibility of infill wells, indicating the timeframe during which the option for infills opens and closes.

The probability of successfully accessing the remaining reserves in mature fields

Numerous studies in the literature on the upstream industry indicate that they contribute to improved decision-making. However, these studies often lack clarity regarding the mechanisms through which this improvement occurs. Furthermore, a majority of these investigations do not employ consistent decision analytics methods. Quantifying uncertainties and translating them into probability emerges as the most significant challenge in applying decision-making methodologies in the upstream and specifically in drilling operations. Despite significant efforts in uncertainty quantification, the probability function remains undisclosed, hindering proper assessment and subsequently impeding its utilization in the decision-making process. In heavily depleted mature fields, accessing the remaining reserves with conventional overbalanced drilling (OBD) becomes impossible due to geological changes (Bernt Sigve Aadnoy, 1991). Alternatively, underbalanced drilling (UBD) can be employed to access the remaining reserves. UBCTD offers the advantages of eliminating formation damage, thereby promoting productivity improvement and incremental recovery (Cade et al., 2003). There is an inherent risk of formation collapse, which can lead to failure to reach the target, representing a worst-case scenario. Academia and industry members endeavoured to define the problem through analytical and statistical models. Some statistical models succeeded in identifying the problem based on specific historical data, but the interrelation between variables is never explained, and extrapolation of results for different fields proved unreliable. Additionally, experts cannot assign a probability for this issue due to its complexity and the involvement of multiple variables. Furthermore, historical data may not accurately represent the current state of the fields due to geological evolution. Conversely, analytical models don't consider the factors that can't be translated by physics and mathematics, such as human errors. In our practical approach, we rely on mathematical models and use the general range of inputs that can be adjusted by experts' opinions.

The field of geomechanics within the literature of wellbore instability addresses this particular issue. Uncertainty in wellbore stability arises from inherent uncertainties in input data for computed factors and uncertainties in the measurements of directly measured factors (Bernt S. Aadnoy, 2011). A deterministic estimate of these factors offers only single-point values. Instead, employing probability distributions in inputs for a geomechanics model allows the quantification of cumulative uncertainties in the outputs, thereby enhancing the decision-making process. Previous works have provided valuable insights into understanding uncertainties in wellbore stability such as Udegbunam et al., (2013). However, some studies lack a clear demonstration of the probability of success/failure, while others may reveal such probabilities without providing guidance on how to integrate them into the decision-making process. We contribute to the mentioned literature by providing transparent framework necessary for consistent operational decisions as shown in Figure (4).

An attempt is made for the development of a deterministic mathematical model and the definition of the probability distribution of inputs. Subsequently, Monte Carlo simulation is employed to ascertain the distribution of outcomes (Udegbunam et al., 2013). The purpose of the stochastic model is to record instances where bottom hole pressure falls below the collapse pressure. This count is then divided by the total number of Monte Carlo simulations, yielding the frequency or probability of encountering collapse conditions as illustrated in Figure (3). It's essential to clarify that this process doesn't constitute true probability elicitation but rather serves as an indication of the likelihood of events occurring, based on numerical counts. The conventional deterministic approach commonly utilized by drilling practitioners typically fails to account for the uncertainties associated with various factors. Consequently, it lacks the ability to facilitate an informed decision-making process. Conversely, the probabilistic approach reveals the uncertainties linked to these factors within a defined range of inputs, enabling more informed decisions.

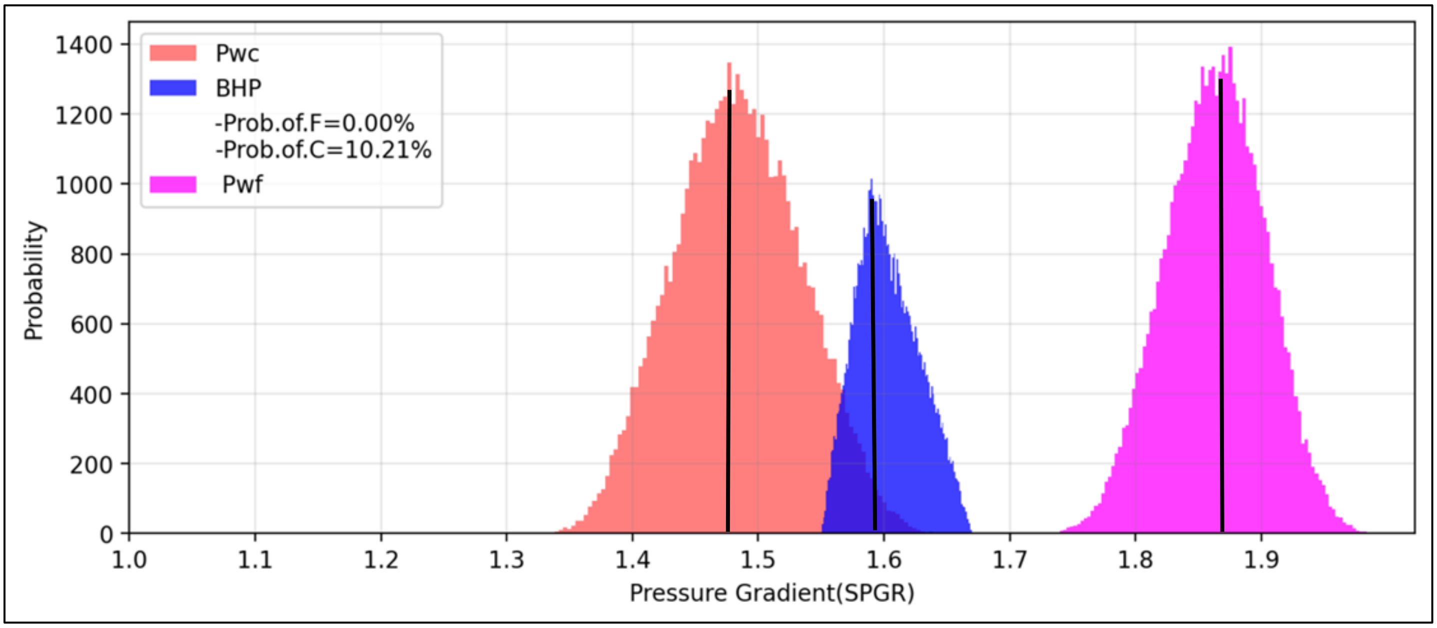


Figure 3: This figure illustrates the deterministic versus probabilistic approach in determining the uncertainty in collapse, bottom hole pressure (BHP), and fracture pressure. It also shows the overlap between collapse and BHP, which is expressed as the chance of failure (implemented in Python).

We utilize the mentioned probability in a consistent decision framework to facilitate the decision-making process as shown in Figure (4).

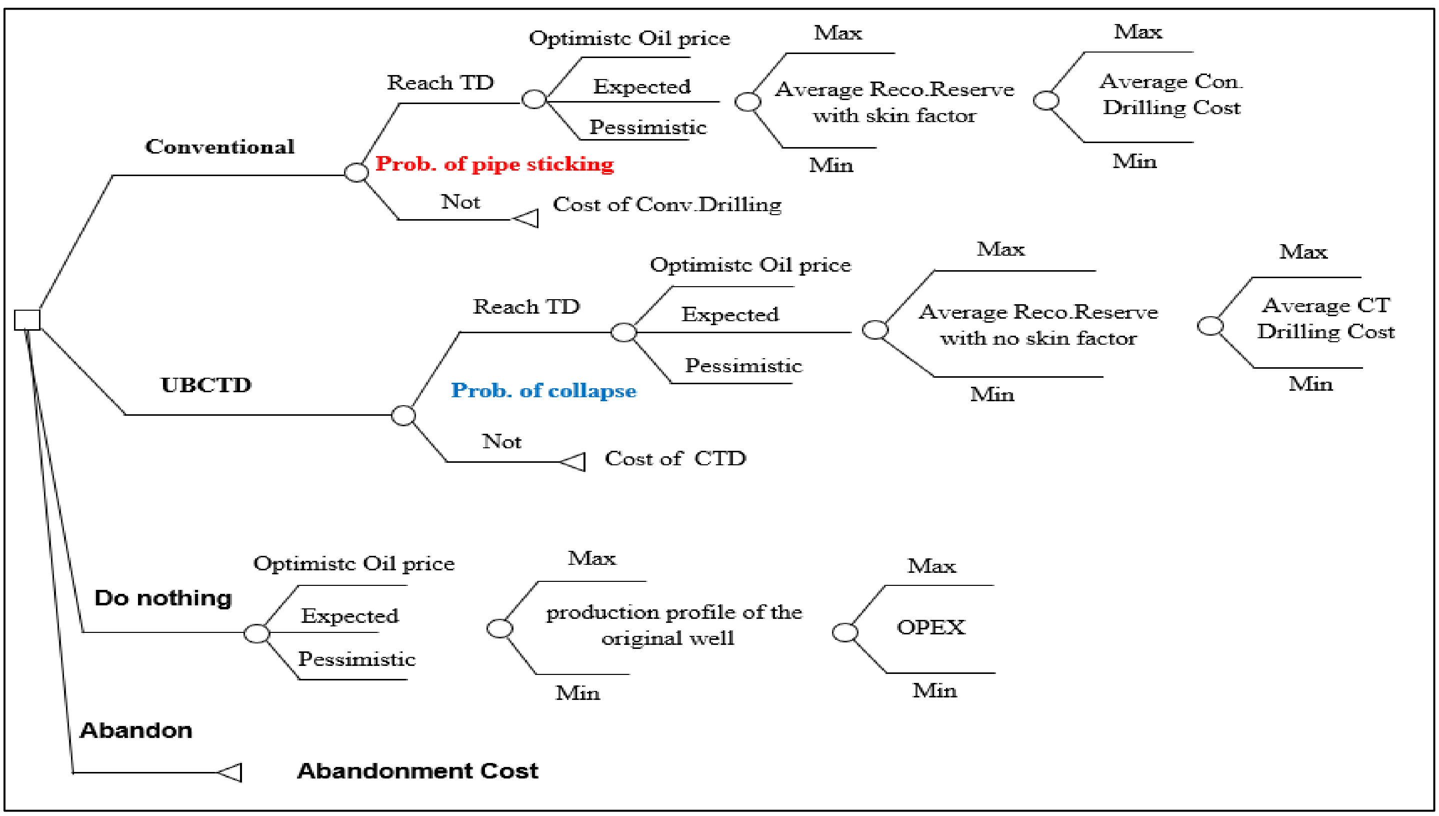


Figure 4: integrated decision model includes uncertainties of different natures.

Oil Price Uncertainty

The mean-reverting price process holds significant theoretical appeal. When markets are in equilibrium, higher prices act as an incentive for high-cost oil producers to enter the market, resulting in an increased supply that eventually pushes prices down toward the mean level. Conversely, lower prices prompt expensive oil producers to exit the market, leading to reduced supply and pushing prices upward. This dynamic interplay between price, supply, and demand contributes to the mean reversion behaviour observed in oil prices. This relationship has been thoroughly examined and recognized for its role in underlying factors influencing fluctuations in oil prices (Pindyck, 1999). By understanding and modelling this mean reversion behaviour, we gain a deeper comprehension of how oil markets respond to changing conditions and how prices tend to revert to their long-term average over time.

While multifactor models may provide more accurate representations of price dynamics, they come with increased complexity in their formulation and interpretation. On the other hand, single-factor models are easier to work with and understand, making them practical tools for decision-makers, especially in scenarios where a quick and clear assessment of oil price behaviour is needed. Moreover, in the oil and gas industry, operators often prefer using one-factor models to facilitate effective communication (Jafarizadeh & Bratvold, 2019).

The mean-reverting process consists of two components: an assumed constant average value and a short-term stochastic deviation. These deviations fluctuate randomly around zero, with positive values indicating higher-than-average spot prices and negative values representing lower-than-average prices. Mathematically, the spot price S_t at time t follows the process $\ln(S_t) = \chi_t + \xi_t$, where ξ_t represents the time-independent average level, and short-term deviations $\chi_t$follow an Ornstein-Uhlenbeck process.

$$d\chi_t = -\kappa\chi_t dt + \sigma dz \quad (1)$$

Here κ represents the mean reversion coefficient, σ is the standard deviation for the short-term factor, while dz is the increment of the standard Brownian motion. A higher mean-reversion coefficient implies that short-term deviations dissipate more rapidly. Additionally, increased volatility indicates that we anticipate more significant fluctuations around the average price level.

The value of a forward contract ($F_{t,T}$) for the delivery of a barrel of oil at a time (t), set for delivery at (T), is determined by the spot price and, consequently, influenced by the variable (x_t).

$$F_{t,T} = \mathrm{e}^{-k(T-t)}x_t + \xi + \left(1 - \mathrm{e}^{-2k(T-t)}\right)\frac{\sigma^2}{4k} \quad (2)$$

The binomial-lattice representation of a continuous mean-reverting process has been derived and presented by Hahn & Dyer, (2008). The subsequent equations illustrate the derivation of these expressions.

Within the time interval (Δt), the price represented by the variable (x) can move upwards to the value (x_{t+}) with a probability of price up (p_u), or it can move downwards to the value (x_{t-}) with a probability of price down (p_d).

$$x_{t+} = x_t + \sqrt{\Delta t\sigma} \quad (3)$$

$$x_{t-} = x_t - \sqrt{\Delta t\sigma} \quad (4)$$

$$p_u = max\left(0, min\left(1, {}^1/_2 - \sqrt{\Delta}t\left(kx_t + {}^1/_2\,\sigma^2\right) / 2\sigma\right)\right) \quad (5)$$

$$p_d = 1 - P_u \quad (6)$$

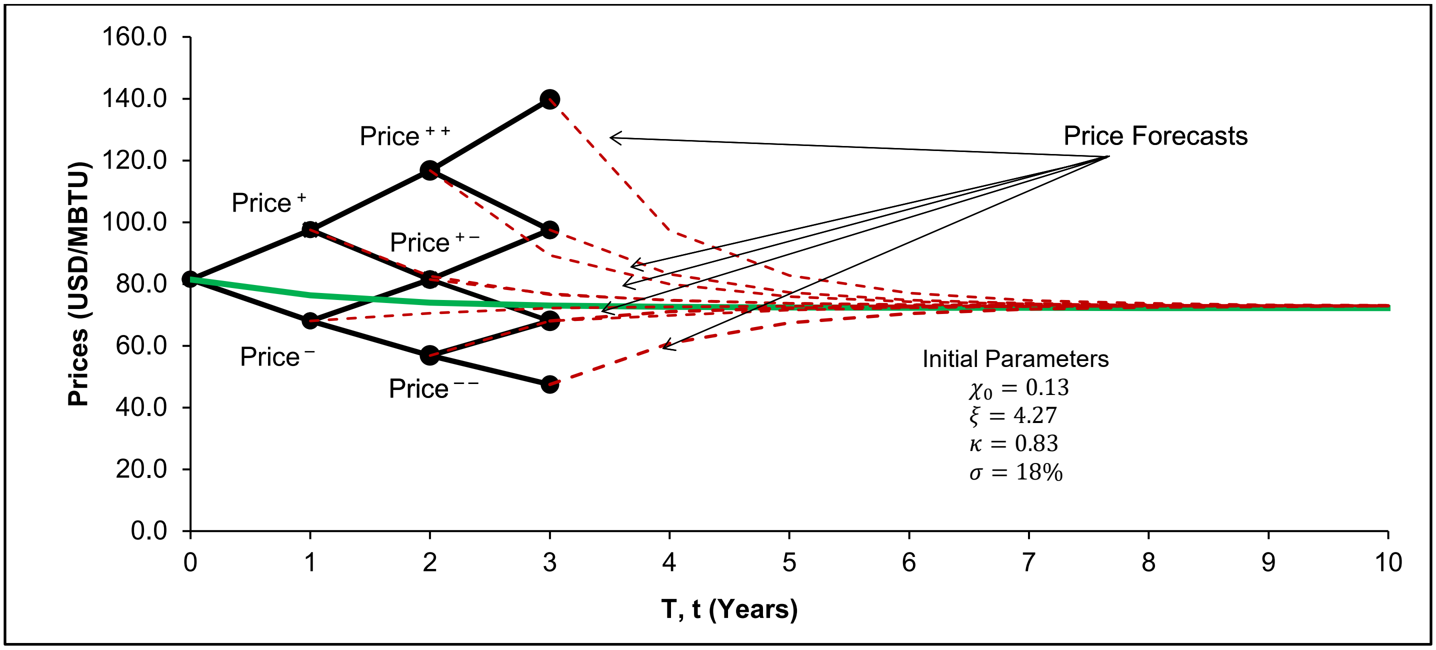


Figure 5: The binomial process of oil price and the forward curves, originating from each decision point.

In each period, the probabilities are contingent on (χ_t), which represents the deviation from the mean. Additionally, Equation 5 constrains these probabilities within the range of zero to one.

The decision window opens at the decline of production and extends until reaching the economic threshold. Throughout this period, operators periodically reassess the economic viability of decisions, considering the fluctuation in oil prices and value from production cash flows. We use forward price dynamics to assess the value from production. Our binomial lattice begins from the point at which this opportunity window opens.

At the outset of the binomial lattice $t = \tau$, χ_τ is the function of time τ and its initial value is x_0. As the mean value remains constant, alterations in future prices arise from fluctuations in short-term deviations. Consequently, the values of (χ_τ) can be employed as representatives of future prices, where $\chi_\tau - x_0 = ln\, F_{0,0}$.

$$\chi_\tau = \mathrm{e}^{-k\tau} x_0 + \xi + (1 - \mathrm{e}^{-k\tau}) \frac{\sigma^2}{4k} - x_0 - \xi + \chi_0 \qquad (7)$$

$$\chi_\tau = \mathrm{e}^{-k\tau} x_0 + (1 - \mathrm{e}^{-k\tau}) \frac{\sigma^2}{4k} \qquad (8)$$

Markov Decision Approach

During the declining phase in depleted mature fields, the field operator assesses decisions including drilling re-entries, permanent abandonment, or waiting. Despite the declining production, the field's value is influenced by fluctuations in oil prices. At specific stages, managers analyse the projected future prices and make their decision. Opting to wait entails monitoring prices for an additional period and confronting the same set of decisions as shown in Figure (6). Typically, this process is repeated on an annual basis with updated oil prices. The open-ended lines indicate the continuation.

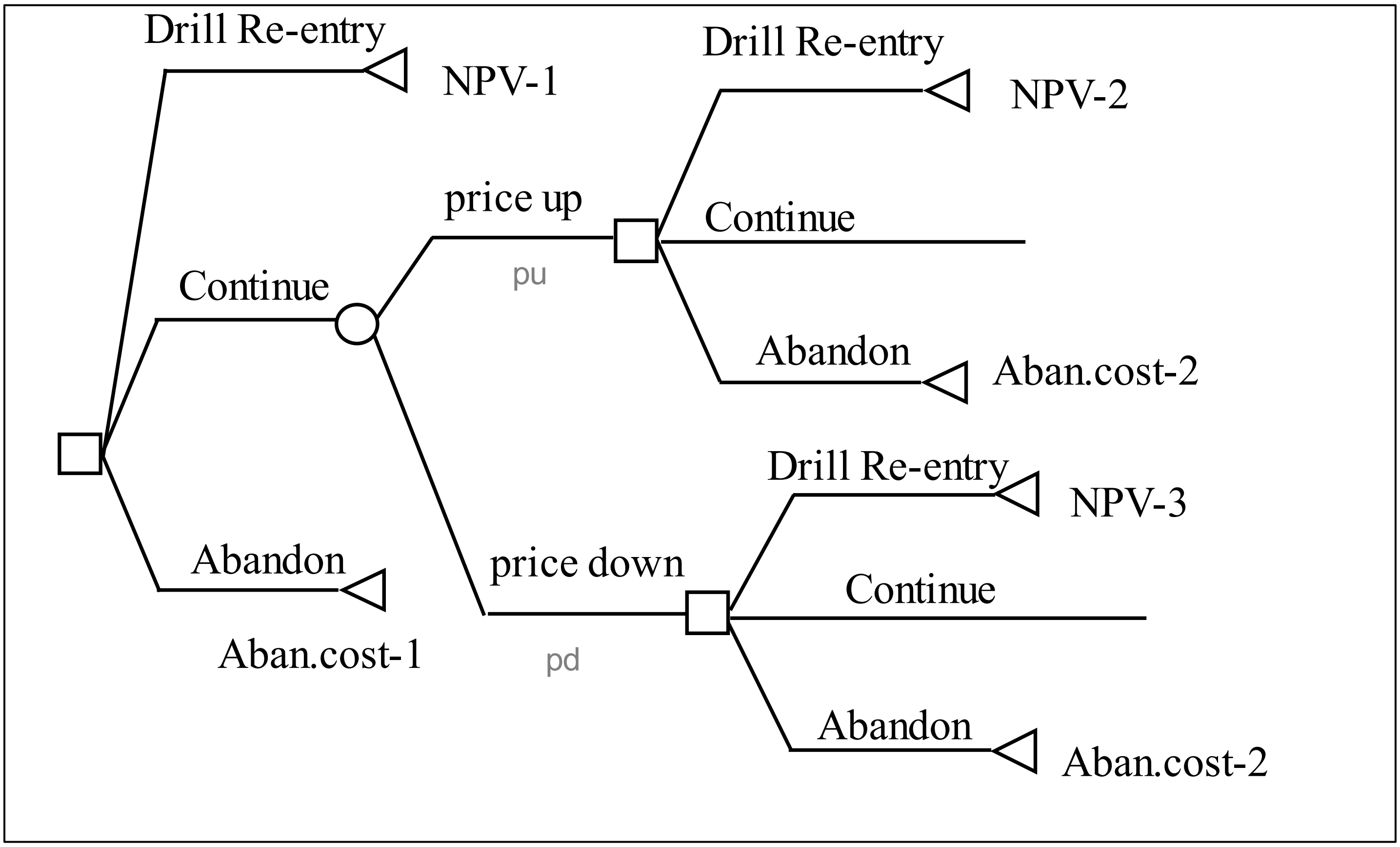


Figure 6: this figure depicts the dynamic decision approach, highlighting the annual decisions and their updated probability of occurrence.

Conducting re-entries in mature fields comes with opening time (T) and closing time (t) for the opportunity window. Early or delayed re-entry may be infeasible. In heavily fractured, faulted, and depleted reservoirs, underbalanced drilling becomes the only method to access the remaining reserve. As the severity of depletion increases, accessing the remaining reserve becomes more challenging. During underbalanced drilling, two distinct challenges arise that could jeopardize the value of this drilling technique: the inherent risk of formation collapse and the operational risk of failure in sustaining the underbalanced condition at the bottom. Nevertheless, UBCTD demonstrates high efficiency in managing unbalanced conditions. Consequently, the sole risk stems from the probability of formation collapse. Extending field life through re-entry drilling delays abandonment costs, yielding discounted benefits. Alternatively, if the economics are unfavourable, immediate field abandonment is an option. These decisions typically rely on the economic threshold, determined by future oil price projections. We consider the future contracts to be a risk-neutral predictor of future price trends and use them for fitting the parameters of mean reversion process. Additionally, managers are presumed to utilize forward curves for assessing the expected discounted payoffs of their decisions.

The forward curve within a mean-reverting process is characterized by its dependence on the parameter (χ_t), allowing us to establish a deterministic payoff function $g(\chi_t)$ at every decision point. As (χ_t) exhibits Markov properties (its present value is independent of its past values), the value of the option at each time point (V_t) will similarly rely on (χ_t), denoted as $v_t(\chi_t)$, therefore $V_t = v_{t(\chi_t),}$ $t = \tau, \tau + 1$.

As the opportunity window approaches its close point at time ($t = T$), given the diminishing value of the field, managers are tasked with making the optimal decision to either continue, abandon, or undertake re-entry drilling, and obtaining $g(\chi_T)$. Within the timeframe of the window ($\tau < t < T$), managers assess the exercise value

($g(\chi_t)$) against the anticipated value of continuing to the next year. Commencing from time T, the valuation procedure follows a recursive algorithm, demonstrated in Equations (9) and (10).

$$V_T(\chi_T) = max(g(\chi_T), NPV^{x_T} Continue) \quad (9)$$

$$V_t(\chi_t) = max\big(g(\chi_t), 1/(1+r)\big(Pu\ v_{t+1}(\chi_t^+) + pd\ v_{t+1}(\chi_t^-)\big) + CF_t \quad (10)$$

When $\tau < t < T$, r is the discount rate, and $g(\chi_t)$ is the net present value of the option (abandonment or re-entry) at time (t). τ and T represent the opening and closing time respectively.

$$g(\chi_t) = max(NPV^{xt} Abandonment, NPV^{xt} Reentry) \quad (11)$$

When (NPV^{xt}) denotes the net present value (NPV) at time (t) for the total cash flows derived from that specific course of action, subject to the condition of (χ_t). If the managerial decision is to proceed, (CF_t) represents the cash flow for the production profile of the original wells. This recursive algorithm in equations (9 to 11) determines the value of either re-entering or abandoning the oil field at the initiation of the option window ($t = \tau$).

The overall project value, denoted as (V_0), comprises both the option value ($v_\tau(x_\tau)$) at the opening window and the discounted cash flow before the option within the range of ($0 \leq t < \tau$) as shown in equation (12).

$$V_0 = \sum_{t=0}^{\tau} \frac{CF_t}{(1+r)^t} + \frac{v_\tau(\chi_\tau)}{(1+r)^\tau} \quad (12)$$

The system's progression is driven by prices adhering to a mean-reverting process, and the stopping rule presents two choices: an immediate field abandonment or accessing the remaining reserves now with a delayed cost of abandonment. Continuing entails persisting with the ongoing production decline. In our specific scenario, the costs and benefits are not straightforward, instead, they comprise a sequence of cash flows that we evaluate through our dynamic forward curve estimation.

Illustrative Example

The provided example depicts the valuation procedure for a re-entry well (open hole) that is assumed to be drilled in an onshore reservoir in the USA. The initial oil well is in the declining phase and projected to produce for a span of six years, with the choice to either re-entry or abandon it during the second, third and fourth years of the decline. Within our evaluation process, we consider certain technical and economic assumptions as outlined below:

Technical inputs:

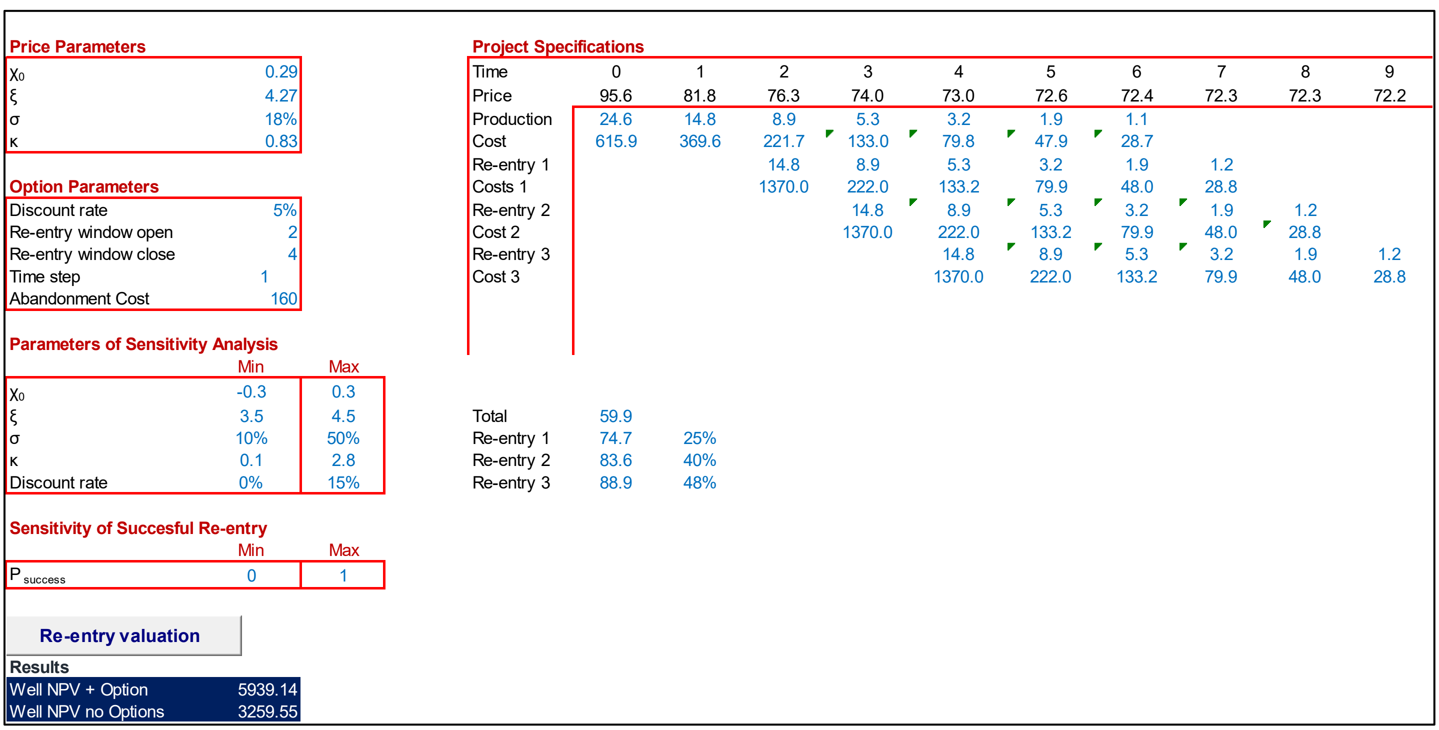
- The initial well experiences a decline from 80 barrels per day (15% of annual shutdown for workover), diminishing by 40% each year. The projected economic limit for the original well is expected to occur in the sixth year. The re-entry well is targeting an isolated pocket in a tight reservoir and experiences an identical decline rate of 40%.
- The drilling cost (CAPEX) for a re-entry well amounts to $1 million, reflecting the average open-hole drilling expenses within a USA-based onshore field. This value is determined by considering the average cost-saving factor of (34%) associated with the use of Coiled Tubing Drilling (CTD) in comparison to conventional drilling methods.

- The operational expenditure (Opex) is estimated at \$22 per barrel, which is the average observed in onshore fields across the USA. This data is sourced from the U.S. Energy Information Administration (EIA) report from 2016.
- The cost for abandonment is set at \$160,000 per well, representing the p90 in onshore USA scenarios (Raimi et al., 2021).
- We assume the probability of experiencing formation collapse in underbalanced drilling is 10.4% using the range of magnitudes that mentioned in Udegbunam et al., (2013).
- The average accessible depth and horizontal length globally achieved through Coiled Tubing Drilling (CTD) is clarified in the Appendixes.

Economic inputs:

- Oil price is forecasted using a geometric mean-reverting process.
- Model parameters are determined through fitting with future contracts.
- We use risk-free discount rate , considering the risk-neutral application in oil and gas industry (Smith & Mccardle, 1999).
- A Markov chain model is updated version based on the approach outlined in (Jafarizadeh & Bratvold, 2019).

In this scenario, the production decreases after the plateau to a point where the managers must consider abandoning, continuing, or re-accessing the reservoir. The decision is influenced by the fluctuating value of the field caused by changes in oil prices. The critical question is: When is the optimal time to take an action, and which course of action maximizes the project value?



Price Parameters

χ_0	0.29
ξ	4.27
σ	18%
κ	0.83

Option Parameters

Discount rate	5%
Re-entry window open	2
Re-entry window close	4
Time step	1
Abandonment Cost	160

Parameters of Sensitivity Analysis

	Min	Max
χ_0	-0.3	0.3
ξ	3.5	4.5
σ	10%	50%
κ	0.1	2.8
Discount rate	0%	15%

Sensitivity of Succesful Re-entry

	Min	Max
$P_{success}$	0	1

Re-entry valuation

Results

Well NPV + Option	5939.14
Well NPV no Options	3259.55

Project Specifications

Time	0	1	2	3	4	5	6	7	8	9
Price	95.6	81.8	76.3	74.0	73.0	72.6	72.4	72.3	72.3	72.2
Production	24.6	14.8	8.9	5.3	3.2	1.9	1.1			
Cost	615.9	369.6	221.7	133.0	79.8	47.9	28.7			
Re-entry 1			14.8	8.9	5.3	3.2	1.9	1.2		
Costs 1			1370.0	222.0	133.2	79.9	48.0	28.8		
Re-entry 2				14.8	8.9	5.3	3.2	1.9	1.2	
Cost 2				1370.0	222.0	133.2	79.9	48.0	28.8	
Re-entry 3					14.8	8.9	5.3	3.2	1.9	1.2
Cost 3					1370.0	222.0	133.2	79.9	48.0	28.8

Total	59.9	
Re-entry 1	74.7	25%
Re-entry 2	83.6	40%
Re-entry 3	88.9	48%

Figure 7: The program interface of the valuation model for the re-entry option, all values are multiplied by 1000.

This figure illustrates the program interface that integrates projected production profiles, cost considerations, price parameters, operation parameters, abandonment cost, and geological probability of success, all of which collectively influence the project's value.

In this valuation, the overall value of any option is the summation of its value at (t=2) and the cash flow preceding the option when t < 2. In simpler terms, the Net Present Value (NPV) of the project equals the sum of the value derived from the binomial lattice and the value preceding the binomial lattice. Equation 14 is utilized to calculate the NPV of this option, resulting in a value of 5,939,000 USD. For $t \geq 2$, the binomial lattice methodology is utilized to calculate the remaining portion of the project's value. Equations (9,10 & 11) are used for this process.

Applying the methodology discussed earlier, we compute the value of the re-entry option as follows. At t = 1, as shown in Equation (8), (χ_t) decreased from 0.29 to 0.13. Subsequently, by utilizing Equations (3) through (6), we establish a binomial lattice to depict the evolution of (χ_t). By the time t = 4 is reached, and after three intervals, (χ_t) could range from a low of (-0.41) to a high of 0.67. Utilizing this data, we formulate forward curves for each (χ_t) and estimate the value of each alternative decision. The recursive algorithm described in Equations (9) through (11), yields an option value of 3,570,000 USD as shown in Figure (7).

NPV (The value of the best)			
t1	t2	t3	t4
3570.40	4003.35	1718.23	311.74
0.00	3705.70	1529.11	191.50
0.00	0.00	1360.32	141.53
0	0	0.00	97.90

Chi-lattice			
t1	t2	t3	t4
0.13	0.31	0.49	0.67
0.00	-0.05	0.13	0.31
0.00	0.00	-0.23	-0.05
0.00	0.00	0.00	-0.41

NPV (Re-entry option)			
t1	t2	t3	t4
0.00	4003.35	1718.23	311.74
0.00	3705.70	1529.11	191.50
0.00	0.00	1360.32	84.34
0.00	0.00	0.00	-11.44

NPV (Continue)			
t1	t2	t3	t4
0.00	914.77	511.90	248.53
0.00	774.27	422.01	191.41
0.00	0.00	343.35	141.53
0.00	0.00	0.00	97.90

Figure 8: The result of the binomial lattice for chi lattice, re-entry option, continuation, and the best option.

This diagram mimics the scenarios analysed by a decision analyst. It initiates at the decision point and illustrates the likelihoods of oil prices either increasing or decreasing. The forward curves originate from each of these points. Certain time-based restrictions are in place, ensuring that the probabilities of price increases and decreases remain within reasonable bounds. If the probability of a price increase becomes more than three times the original value enters an impractical range. Nevertheless, this model takes into account three time periods.

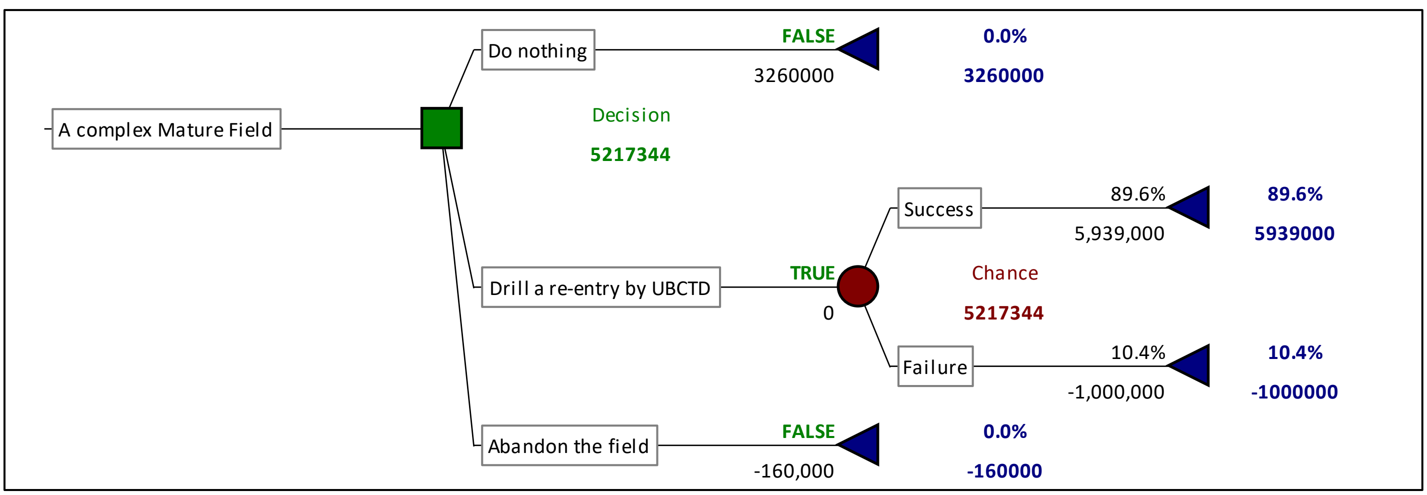


Figure 9: Resolved decision tree incorporating options, probabilities, and outcomes.

Discussion

We employ the discrete version of mean reversion model to generate arrays of forward prices. Each decision point originates from a time step representing the probability of the price either rising or falling, along with its initial value. These prices, in turn, are utilized to calculate the NPV for the best decision alternatives, including abandonment or re-entry for the duration of the production period. This automated process is efficient even for large-scale problems. Our sensitivity analyses demonstrate the effects of altering price and project parameters on the value of the re-entry option, as depicted in Figures (9) and (10).

Our model highlights that accessing the remaining reserve through UBCTD before the field reaches its economic limit can yield additional value, particularly when capitalizing on favorable oil prices. Nonetheless, the most advantageous decision is contingent upon both the declining rate of the original wells and the projected future oil price within the option window.

Based on mean-reverting behavior of prices, initiating from a position of high oil prices makes the early re-entry option more favorable, driven by the anticipated decrease in oil prices and declining pressure of the field. However, when the current spot oil price falls below the average, opting for a later decision might be more advantageous because the upcoming prices are expected to rise. Additionally, the discounted value of the abandonment cost plays a role in delaying abandonment, thereby enhancing the overall value. Other factors are bounded the decision including the declining production rate of the original wells, the economic limit, geological limitations, and the potential recovery from the re-entries.

A sensitivity analysis of the probability of success reveals that drilling a re-entry well by UBCTD is viable only when the probability of success exceeds 50%. Otherwise, it is more advantageous to stick with the original production strategy. The breakeven point is the threshold at which the re-entry option yields a higher (NPV) than doing nothing. Additionally, the discount rate has minimal impact on the total value due to the rapid production decline of the tight reservoir that coincides with the sharp decrease in oil prices. Given that greatest oil production occurs in the initial stages, the subsequent values are less affected by the discounting impact. The project value is most significantly influenced by changes in oil prices. Moreover, as volatility rises, the project value increases. Conversely, a higher mean reversion coefficient leads to a decrease in the project value as shown in Figure (10).

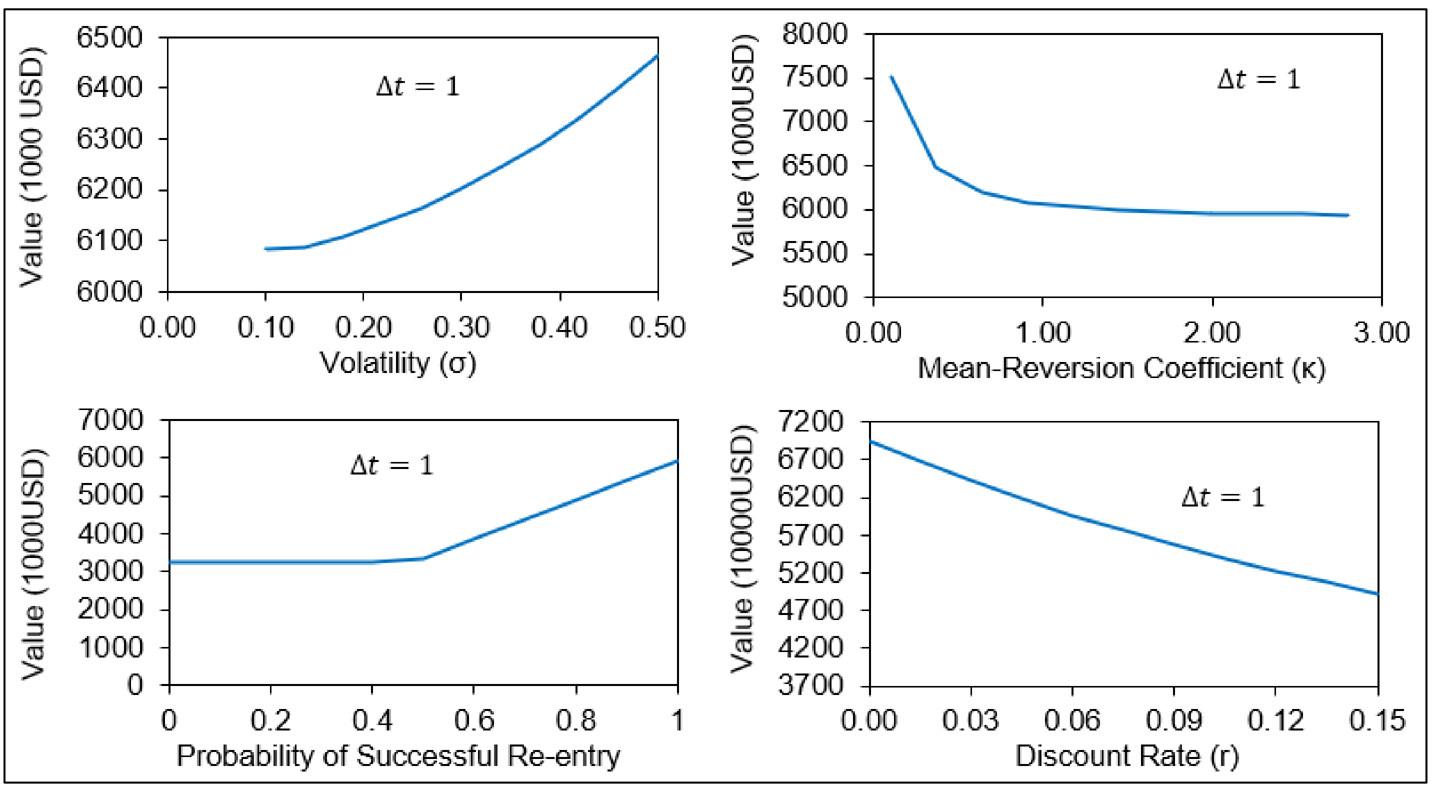


Figure 10: Sensitivity analysis for volatility, mean reversion coefficient, probability of success, and discount rate.

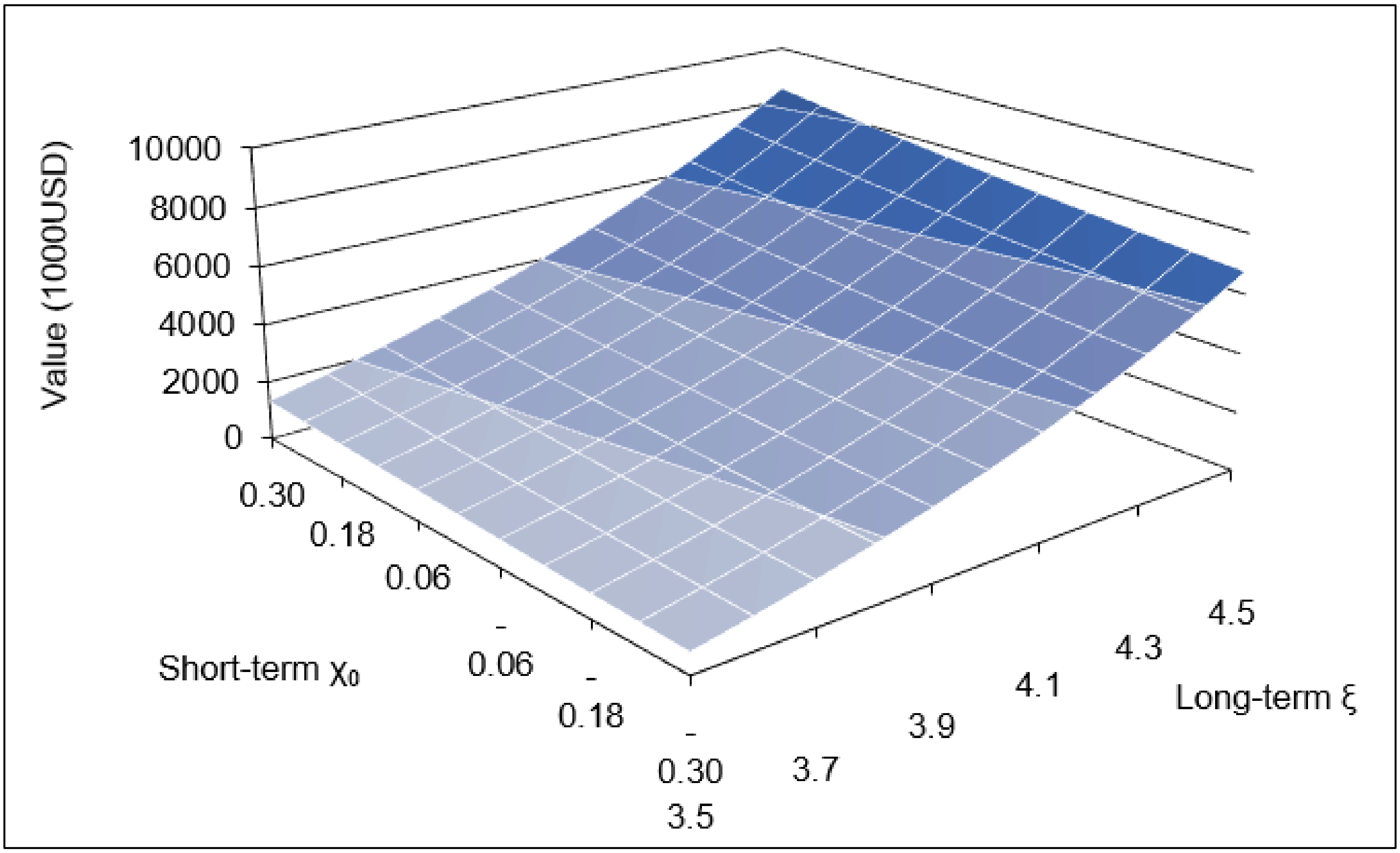


Figure 11: depicts the three-dimensional sensitivity analysis of the short- and long-term variables of mean reversion process with the project value.

Conclusion

The decision to use underbalanced coiled tubing drilling to access the remaining reserve in mature oil fields is affected by geological and market uncertainties. The assessment is applied in an integrated model, encompassing not only the value of flexibility of this option but also the other operational options such as continuing with the declining value or permanent shutdown. For optimizing the decision, we offer a consistent evaluation model that considers consistent oil price outlook, geological uncertainties that expressed as probability of success in reaching the target, drilling cost, and the potential recovery of the re-entry. The cost, probability of success, and potential recovery of UBCTD has been derived from the literature.

We model oil price dynamics using a mean-reverting process within a binomial lattice framework. At every node within this lattice, a forward curve is created, allowing to approximate the anticipated value for each potential decision. Subsequently, a recursive algorithm is employed to compute the valuation of each option, whether to proceed with the declining value, drilling re-entries, or opting for abandonment. This model provides a consistent tool for making an informed decision for infill drilling in mature fields. It stands out for its simplicity and versatility, allowing to accommodate realistic production profiles and deliver outcomes within seconds. Moreover, the model incorporates sensitivity analysis of the key variables.

Future work

Further effort is needed for the consistent elicitation of the probability of success. Additionally, investigating uncertain recoverable reserves and optimizing the number of wells under uncertainty are crucial areas for further research.

References

Aadnoy, Bernt S. (2011). Quality assurance of wellbore stability analyses. *SPE/IADC Drilling Conference, Proceedings*, *2*, 851–861. https://doi.org/10.2118/140205-ms

Aadnoy, Bernt Sigve. (1991). Effects of reservoir depletion on borehole stability. *Journal of Petroleum Science and Engineering*, *6*(1), 57–61. https://doi.org/10.1016/0920-4105(91)90024-H

Al-Sharea, M. F. (2024). The Value of Underbalanced Coiled Tubing Drilling UBCTD in Unconventional Mature Fields: Decision Analytic Approach. *Proceedings - SPE International Symposium on Formation Damage Control*, *2024-February*. https://doi.org/10.2118/217890-MS

Begg, S., Bratvold, R., & Campbell, J. (2002). The Value of Flexibility in Managing Uncertainty in Oil and Gas Investments. *Proceedings - SPE Annual Technical Conference and Exhibition*, 2165–2174. https://doi.org/10.2523/77586-ms

Burke, J., Eller, G., Venhaus, D., & Gantt, L. (2014). Coiled tubing drilling: Increasing horizontal reach in the kuparuk field. *Society of Petroleum Engineers - Coiled Tubing and Well Intervention Conference and Exhibition 2014*, 193–204. https://doi.org/10.2118/168250-ms

Cade, R., Kirvelis, R., Nafta, M., & Jennings, J. (2003). Does underbalanced drilling really add reserves? *Society of Petroleum Engineers - IADC/SPE Underbalanced Technology Conference and Exhibition 2003, UTCE 2003*. https://doi.org/10.2523/81626-ms

Doremus, D. M., & Dowell, S. (1995). *Technical and Economical Feasibility of Coiled Tubing Drilling*. 405–413.

Hahn, W. J., & Dyer, J. S. (2008). Discrete time modeling of mean-reverting stochastic processes for real option valuation. *European Journal of Operational Research*, *184*(2), 534–548. https://doi.org/10.1016/j.ejor.2006.11.015

Iadc, S. P. E., Krueger, S., Gray, K., Killip, D., & Hughes, B. (2013). *Fifteen Years of Successful Coiled Tubing Re-entry Drilling Projects in the Middle East : Driving Efficiency and Economics in Maturing Gas Fields*.

Jafarizadeh, & Bratvold. (2019). The option value of refracturing oil wells: Implementation in a binomial lattice. *SPE Journal*, *24*(4), 1903–1911. https://doi.org/10.2118/195585-PA

Johnson, M., Brand, P., French, S., Sarber, G., Hildreth, D., Harris, B., Rangel, P., Cassee, U., & Clark, J. (2008). Coiled-tubing underbalanced drilling in the Lisburne field, Alaska. *JPT, Journal of Petroleum Technology*, *60*(6). https://doi.org/10.2118/0608-0079-jpt

Krueger, S., & Pridat, L. (2016). Twenty years of successful coiled tubing re-entry drilling with e-line BHA systems - Improving efficiency and economics in maturing fields worldwide. *Society of Petroleum Engineers - SPE/ICoTA Coiled Tubing and Well Intervention Conference and Exhibition*. https://doi.org/10.2118/179046-ms

Lund, M. W. (2000). Valuing Flexibility in Offshore Petroleum Projects. *Annals of Operations Research*, *99*(1–4), 325–349. https://doi.org/10.1023/a:1019284119505

O'Brien, J., Sayavedra, L., Mogollon, J. L., Lokhandwala, T., & Lakani, R. (2016). Maximizing mature field production - A novel approach to screening mature fields revitalization options. *78th EAGE Conference and Exhibition 2016: Efficient Use of Technology - Unlocking Potential*. https://doi.org/10.2118/180090-ms

Pindyck, R. S. (1999). The Long-Run Evolution of Energy Prices. *The Energy Journal*, *20*.

Raimi, D., Krupnick, A. J., Shah, J., & Thompson, A. (2021). *Decommissioning Orphaned and Abandoned Oil and Gas Wells: New Estimates and Cost Drivers*. https://doi.org/10.1021/acs.est.1c02234

Smith, J. E. (2005). Alternative Approaches for Solving Real-Options Problems. *Decision Analysis*, *2*(2), 89–102. https://doi.org/10.1287/deca.1050.0041

Smith, J. E., & Mccardle, K. F. (1999). Options in the real world: Lessons learned in evaluating oil and gas investments. *Operations Research*, *47*(1), 1–15. https://doi.org/10.1287/opre.47.1.1

Udegbunam, J. E., Arild, Ø., Fjelde, K. K., Ford, E., & Lohne, H. P. (2013). Uncertainty based approach for predicting the operating window in UBO well design. *75th European Association of Geoscientists and Engineers Conference and Exhibition 2013 Incorporating SPE EUROPEC 2013: Changing Frontiers*, *December*, 2012–2024. https://doi.org/10.2118/164916-ms