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Loss Circulation Prevention during Drilling Operation - Risk Analysis Approach and its Implications

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Abstract. Drilling engineers and operators are stuck with challenges associated with loss circulation of drilling fluids in wellbores during drilling operation. At such times, a clear and careful decision is required in order to minimize cost or save resources that would have been lost in the bid to remedy the situation. This then informs the need to deploy reliable tools that will inform useful decisions as drawn from a thorough risk-analysis coined from the information gathered from the formation characteristics and operating pressure. In this study, a real-time statistic based approach was adopted in carrying out risk-evaluation of loss circulation events in a wellbore. Based on the expected opportunity loss analysis, it is often non-negotiable to consider other options when the analytical solution suggests that the well should be "abandoned". For the decision tree, at the decision node, D_1, the expected loss of the seal off zone option is $161.25, the expected loss of the drill ahead option is $19.2 and the expected loss of the abandon option is $13.2. Since the expected loss of the abandon option is less than the expected value of both the seal off and the drill ahead option, it is recommended to abandon the well. Furthermore, the risk analysis proved to be a veritable tool considering the cost implications of other options; and can also serve as basis for automated decision-making.

Introduction

Over the years, business risks in the oil sector have increased considerably with its huge rewards; from swamps to onshore, offshore, deep waters and even ultra-deep waters. Though no one likes or plans to lose an investment, many still do, partly due to decision making [1,2]. Therefore, stakeholders are gradually aligning themselves to a new era of optimal decision making using improved methods of risk and decision analysis. However, a new generation of Engineers seems to have been quickly immersed in the wave of the decision methods without understanding its fundamentals, applications, limitations and future prospects. According to Bilim *et al.*, [3], identification, cost analysis and evaluation of parameters driving costs of an operation helps in avoiding increased operational cost and decision analysis. Decision analysis is a general term used for the process of making up one's mind about a particular line of action [4]. Within the petroleum industry, decision analysis is applied to determine which projects can be carried out within the confines of competing available resources. The decision analysis therefore, has a bird's eye view of different scenarios of the project, screens alternative scenarios based on predetermined criteria and then selects the preferred line of project implementation. Usually, decisions are made to maximize value or minimize costs and can be done using deterministic, analytical or probabilistic methods. Most of the loss circulation practical guidelines are not general and are biased towards a particular service company [5].

Lost circulation is the partial or complete loss of drilling fluid and/or cement slurry to the formation during drilling or cementing operations or both. Lost circulation events arise most commonly as a consequence of the method used to drill a well [6]. Traditionally, wells are drilled in an overbalanced condition in which drilling fluid, or mud, is circulated down the drill string, through the bit and up the annulus [7]. Mud weight, or density, is the primary source of hydrostatic pressure in a well. When circulating through the wellbore, the mud contributes to a pressure in the wellbore that can be expressed in terms of the equivalent circulating density (ECD). Although the fluid has several purposes, those most affected by loss circulation are largely caused by the need for hydrostatic pressure in the annulus thus preventing formation fluids from entering the bore hole during the drilling process [8]. Lost circulation may occur at any depth where the total pressure exerted against the formation exceeds the formation breakdown pressure [9]. It is the loss of whole drilling fluid or mud at any depth from the hydrostatic fluid column to the formation. This can be brought by natural or induced causes [10]. Loss circulation/loss of whole drilling mud in the formation gives rise to significant costs and risks to drillers around the world and threatens to pose greater challenges in the future [11]. In the Gulf of Mexico alone, wellbore integrity issues in the form of a stuck pipe, lost circulation, wellbore collapse and sloughing shales account for as much as 44% of the nonproductive time (NPT) that prevents the progress of the drill bit toward its target [12]. The industry is meeting this threat with diverse wellbore strengthening materials that work by different mechanisms but share a common goal: to stop fracture growth and keep drilling mud in the wellbore. Lost circulation is one of the major causes of non-productive time [13, 14]. Alkinani et al., [15] highlighted the importance of statistical analysis in recommending the lost circulation strategy for different fields. Not much literature is available on predicting the cost implication / risk of lost circulation during drilling operation.

This study, the economic risks associated with loss circulation while drilling was evaluated and a decision and risk method that will help the industry make a viable economic decision was proposed. A case study in Niger Delta sandstone reservoir is presented to illustrate insights in evaluating the economic risks associated with lost circulation decision making.

Theory

Lost circulation treatment methods are often based on some factors which includes the lost extent, the zone under consideration, the drilling condition and the properties of the drilling fluid system used for the drilling operation. The non-linear nature and complexity of these parameters have made analytical solutions and risk analysis difficult in addressing lost circulation [16].

Risk analysis branches off from the decision analysis process. It means applying analytical tools to identify, describe, quantify, explain uncertainty and its consequences for petroleum industry projects [17]. In risk analysis, the outcomes of different project alternatives are quantified in terms of probabilities. This avails the investor the right tool to determine if the project risk is worth taking amidst competing for allocation of limited resources. The risk analysis also considers the investor's attitude to risk as per if he is risk-averse, risk seeking or risk neutral to projects in the oil and gas industry, especially at the drilling phase. Researchers have studied cost analysis in mining activities [18, 19]. But, drilling operation has been identified as one parameter that has a large effect on unit costs in exploration and production activity. One of the major challenges encountered during drilling operation at any stage of drilling is loss circulation.

It is not possible to completely prevent loss circulation, because some formations are inherently fractured, cavernous, or highly permeable, and are not avoidable if the target zone is to be reached [20]. If lost-circulation zones are anticipated, preventive measures are taken by treating the mud with Loss Circulation Materials (LCMs) and preventive tests such as the leak-off test and formation integrity test should be performed to limit the possibility of loss circulation [21]. Equations 1 and 2 show the conditions that must be maintained to avoid fracturing the formation during drilling and tripping in, respectively.

$$\lambda_{eq} = \lambda_{sm} + \Delta\lambda_{am} < \lambda_{frac} \quad (1)$$

$$\lambda_{eq} = \lambda_{sm} + \Delta\lambda_{s} < \lambda_{frac} \quad (2)$$

Where λ_{em} = static mud weight, $\Delta\lambda_{am}$ = additional mud weight caused by friction pressure loss in the annulus, $\Delta\lambda_{s}$ = additional mud caused by surge pressure, λ_{frac} = formation-pressure fracture gradient in equivalent mud weight, and λ_{eq} = equivalent circulating density of mud.

Selecting the proper solution is based on the most economically viable option. Three categories are considered in this study and they include:

- Wellbore sealing (that may require special cementing technique)
- Drill ahead without returns
- Abandon the well

Al-Hameedi et al., [22] in their statistical and sensitivity analysis study showed the key parameter as the volume of drilling fluid lost in a formation during drilling; and proposed a set of models to predict and estimate the expected mud loss during drilling operations. Risk and decision analysis in the petroleum industry are often applied in the following areas cost and time estimation, resources and reserves models, production forecasts, cash flow, and so on. Chang et al., [23] highlighted the importance of risk analysis in oil and gas industries operations. Their conclusion showed that risk analysis helps to develop a preventative and mitigative strategies for the oil and gas industries; and the study noted the need to develop, adopt and apply risk evaluation techniques in drilling operations. Lukawski et al., [24] developed a new cost index for US onshore oil and gas wells and used it to infer the cost-depth correlation for wells. Zhang et al., [25] proposed the use of dynamic Bayesian network for quantitative risk assessment for offshore managed pressure drilling (MPD) operations. This risk analysis helped them identify the root causes of the challenges associated with MPD for effective prevention and mitigation measures. Amir-Heidari et al., [26] identified drilling operations as an activity that is associated with high-risk in the exploration and production industry. They proposed methods of identifying strategies in reducing accidents and losses in drilling operations through comprehensive risk assessment. Yost et al., [27] estimated the cost and time of wellbore drilling using parametric studies and identified the uncertainties in the cost components. Sun et al., [28] studied the safety assessment in oil drilling operations based on empirical study and analytic network process; and they concluded that it is necessary to have a more comprehensive assessment of drilling operations. Thus, there is need for valuable tool in estimating cost and early risk assessment evaluation for feasibility studies.

Economic Evaluation

This involves selecting the most economically viable Option, using the Expected Value Analysis. The expected value calculations involve assigning probabilities to random variables and then calculating the probabilistic weighted average of the variables [29].

Mathematically: $E\{X\} = \sum_{i=1}^{n} x_i P(x_i)$ (3)

Where

E{X} = the expectation operator, read as "expectation of"

$P(x_i)$ = denotes $P(X = x_i)$, the unconditional probability associated with variable X.

Using a field in Niger Delta as a case study, while drilling a wildcat well for an oil reservoir in which loss circulation was encountered. The drilling operator had three options for mitigating the risk, and they are to Seal off the zone, Drill ahead, or to Abandon the well. The cost of each option and associated probability are given in Table 1.

Table 1: Cost and Probability for each Mitigation Options.

	Outcome	Probability	Cost, M$
Wellbore sealing	Routine	35%	126
	Troublesome	65%	380
Drill ahead	Routine	85%	245
	Troublesome	15%	436
Abandon	Routine	10%	113
	Troublesome	90%	654

Expected Opportunity Loss (EOL) Analysis

EOL is the difference between an actual profit or loss and the profit or loss that would have resulted if the decision maker had perfect information at the time he or she made the decision. The EOL rule states that the most economically viable alternative out of the available alternatives is the one with the most preferred expected regret (EOL value) [29]. The EOL outcome from the data in table 1, is tabulated in Table 2.

Interpretation of result

Well abandonment option has the minimum EOL value of 13,200. Therefore, this option is selected, because it minimizes the expected opportunity loss. Abandoning the well, in this case, is the most economically viable option. The EOL values in Table 2 also represent the cost of uncertainty for each alternative as 161, 250 and 19, 200 for wellbore sealing and drill ahead respectively.

Table 2: Expected Opportunity Loss (EOL) Computation for the above example.

	Wellbore sealing			Drill ahead			Abandon		
Possible Outcome	**Prob.**	**Cost**	**EOL**	**Prob.**	**Cost**	**EOL**	**Prob.**	**Cost**	**EOL**
Routine	0.35	126,000	41,650	0.85	245,000	0	0.1	113,000	13,200
Troublesome	0.65	380,000	119,600	0.15	436,000	19,200	0.90	564,000	0
Total	**1.0**		**161,250**	**1.0**		**19,200**	**1.0**		**13,200**

Decision Tree Analysis

Decision tree is one of the common probabilistic risk analysis technique. It is a diagrammatic representation of decision situations and can be extremely useful in helping the decision maker to gain a visual understanding of the structure of the problem on hand [30]. Decision trees depict pictorial views of the available courses of action, events outcomes and probabilities associated with their outcomes. It can be used to assist in reaching a decision to maximize the expected monetary value (EMV) or to minimize the expected opportunity lost (EOL) by tracking alternative outcomes of any decision and compare the returns of those alternatives while minimizing the risks involved.

The decision tree in this study has one (1) decision node (to drill) and three (3) chance nodes (outcomes), which are to seal off the thief zone, to drill ahead and to abandon the well (Fig. 1).

The sample calculations are:

Seal Off Zone:	0.35 X 119 = $41.65
	0.65 X 184 = $119.6
	41.65 + 119.6 = ($161.25)
Drill Ahead:	0.85 X 0 = 0
	0.15 X 128 = $19.2
	0 + 19.2 = ($19.2)
Abandon:	0.1 X 113 = $13.2
	0.9 X 0 = 0
	13.2 + 0 = ($13.2)

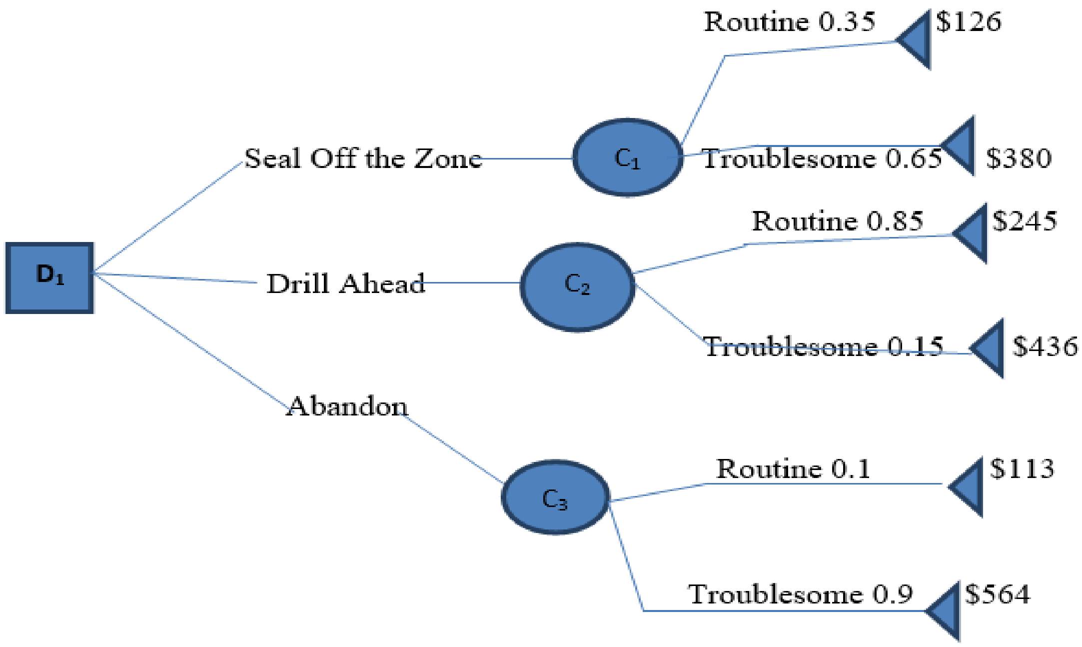

Figure 1: Decision Tree for the Case Study and Three Mitigation Options.

At the decision node, D_1, the expected loss of the seal off zone option is $161.25. The expected loss of the drill ahead option is $19.2; and the expected loss of the abandon option is $13.2. Since the expected loss of the abandon option is less than the expected value of both the seal off and the drill ahead option, it is recommended to abandon the well. If the abandonment option was greater than drill ahead option but less than seal off zone option; then, drill ahead would have been the option for the case scenario.

Accounting for Risk

To account for the magnitude of associated risk in each alternative, the EOL and the standard deviation are used to screen alternatives or as a basis for ultimate choice.
Based on the mean-variance (S^2) approach, the investor who is a risk-averse cost minimizer would choose the alternative that would yield lowest EOL and with the lowest variance [29].

Constructing the Risk Profile

The methods described previously dealt with determining the optimum path in a decision tree. Therefore, a risk profile of the optimum path has to be generated (Table 3).
A risk profile is a distribution function describing the chance associated with every possible outcome of the decision mode.

Since the magnitude of associated risk of the "abandon option" (15.9), is less than the associated risk of both the seal off option (43.3) and the drill ahead option (21.7). Therefore, the "abandon" option is recommended for such well.

Table 3: Risk Profile Table using the EOL and Standard Deviation.

	SEAL OFF THE ZONE					DRILL AHEAD					ABANDON THE WELL				
Possible Outcome	Prob (P_i)	Cost (X_i)	EOL (P_iX_i)	S^2 $P[X_i-E(X_i)]^2$	StdDev	Prob (P_i)	Cost (X_i)	EOL (P_iX_i)	S^2 $P[X_i-E(X_i)]^2$	StdDev	Prob (P_i)	Cost (X_i)	EOL	S^2	StdDev
Routine	0.35	119	41.65	624.8	25	0.85	0	0	313.3	17.7	0.1	132	13.2	11.88	3.4
Trouble-some	0.65	184	119.6	336.4	18.3	0.15	128	19.2	16.3	4	0.9	0	0	156.8	12.5
			161.3		43.3			19.2		21.7			13.2		15.9

Conclusion

There is no guaranteed method for solving lost circulation entirely, but a lot of approaches can be used to prevent its occurrence. Especially those that occur via induced fractures when drilling formations that are prone to losses. This study proposed a method that will eliminate trial and error in making decisions on lost circulation challenges during drilling operation. This proposed method is cost effective and reduces costly downtime that give rise to non-productive time. However, in deciding which mitigation alternative to adopt, the engineer must factor in cost, time and the risk associated with each alternative. Uncertainties and risks are facts of life, and they affect our decisions especially in the oil industry.

Risk and decision analytical methods can help us identify and quantify these risks such that they are better managed. An understanding of statistics and probability are a key requirement for risk analysis models which provide room for good estimation of model parameters as well as describe the randomness or inter-individual variability of the system being modeled. Decision tree and expected opportunity loss (EOL) analysis were used to analysis a well in a Niger Delta field. Well abandonment option has the minimum EOL and decision tree evalution value. Therefore, this option is selected, because it minimizes the expected opportunity loss.

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