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APPLICATIONS OF PROBABILITY OF SUCCESS IN THE WELL DELIVERY PROCESS TO IMPROVE RISK, OPPORTUNITY, AND COST ASSURANCE

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APPLICATIONS OF PROBABILITY OF SUCCESS IN THE WELL DELIVERY PROCESS

TO IMPROVE RISK, OPPORTUNITY, AND COST ASSURANCE

by

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ABSTRACT

Oil and Gas (O&G) well drilling is risky and expensive. The cost of drilling is typically underestimated, and there is little understanding of the certainty or Probability of Success (POS) of achieving the well objectives within the estimated cost. This dissertation presents, for the first time, a publicly available POS Cost method/tool that enables O&G operators to estimate the cost of well drilling substantially more accurately and improve the POS of accomplishing the drilling for the estimated cost. This POS Cost method employs a comprehensive, expert-based assessment of risks and risk mitigations that are incorporated into a Monte-Carlo-based simulation of the well drilling process. Results for applying the POS Cost method/tool to a sample well drilling operation demonstrated that, without employing a risk assessment/risk mitigation approach, the POS Cost of the sample well was roughly 40%, but with the risk assessment/risk mitigation included the POS could be increased to over 80% for an associated cost of roughly 4% for the risk mitigation. Many O&G operators would gladly trade that additional cost for risk mitigation to obtain an 80% POS or greater for accomplishing the well for the estimated cost. This enhances the assurance for the Approval of Expenditures (AFE) and increases the likelihood of successfully achieving the objectives of the well while accounting for time efficiencies due to the incorporations of the mitigation strategies. The POS Cost Tool can also be used to create and evaluate best value options for problem-solving during the drilling process to improve POS for the remainder of the operation.

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With all my love and gratitude,

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Chapter 1 Introduction

1.1 Overview

The Oil and Gas (O&G) industry is divided into three main areas based on the type of activities performed. These are upstream, midstream, and downstream. Historically, the most critical and risk-prone operations are associated with upstream activities. For the upstream activities, the end goal is to ensure that the well delivery process is completed while reducing the well costs and maximizing productivity over the life of the well. The well delivery process is defined as a sequence of activities/stages to plan and execute the drilling and completion of a well (De Wardt, 2010). There is fairly good consensus in the industry on the requirements to determine the monetary value of the well at its early stages (De Wardt, 2010) ((Nzeda & Schamp, 2014) (Olaniran, Love, Olatunji, & Matthews, 2015). Figure 1 presents an example of a well delivery process (or life cycle) for a hydrocarbon project as adapted from Olaniran et al, 2015.

Early in the project's evaluation process, the potential well is evaluated to determine its potential as a good candidate for drilling. The decision to drill is determined by performing several technical and economic analyses. These analyses determine the expected performance of the project and compare its value with other potential opportunities for investment. This stage is usually called "front-end engineering or loading". As per the example case shown in Figure 1-1, the front-end loading constitutes one of the critical stages for value identification. This stage can represent up to 85% of the value of the project (Olaniran, Love, Olatunji, & Matthews, 2015). Other factors that affect capital-investment decisions are the company strategy/policies, acceptance level of risk and uncertainty, and government restrictions. In the early stages, the portfolio is highly dependent on the investment goals of the operator, and it's typically dictated by the assessment of economic indicators such as Net Present Value (NPV), Internal Rate of Return (ROR), Expected Monetary Value (EMV), and technical indicators like geological assessments (oil/gas reserves of the well). However, these projects' returns on Investment (ROI) begin once the well starts producing (see Figure 1-1, end of stage 5). To reach that stage, drilling, completion, and formation evaluation must be conducted successfully, and that is where the financial value of these wells can be the hardest to estimate, and where the largest portion of the project budget is usually allocated.

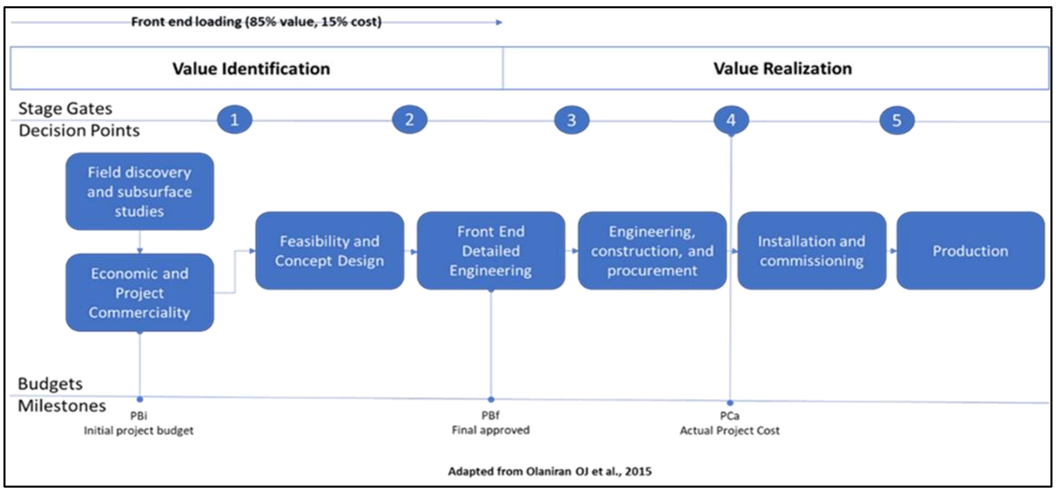

Figure 1-1: Example Life Cycle Process for a Hydrocarbon Project

A recent study shows that the average annual Oil and Gas (O&G) capital expenditure for upstream projects worldwide was slightly over 300 billion U.S. dollars (IEA, 2021). However, despite the large investment, especially in megaprojects (those with a cost of the U.S $1 billion or more), the performance of these projects (Planned vs. Actual Cost) has yet to be noticed. A deep-water exploration well's normal delivery process spans 2 to 5 years, depending on the downhole conditions and technical requirements. It has been found that a significant percentage of the wells attempted in these megaproject cost ranges still need to achieve their planned initial financial and technical objectives. Delays and budget overruns are commonly seen in these projects and are usually associated with their complexity and managing uncertainty and risks. 2019 Ernst & Young Global Limited (EY) analyzed 500 mega projects completed in the previous five years. Out of these, 60% experienced schedule delays, and 38% had cost overruns, usually attributed to the complexity of these projects (Fane, 2020). On the same lines, in a previous report, EY concluded that overruns in megaprojects were due to underestimated risks associated with the projects during the planning (EY, 2014). Similar conclusions were reached by Rui et al. (2016), their study included data collected from 206 O&G projects and found that 74% of the projects underestimated the cost, with an average cost overrun rate of 18.2% of the estimated cost.

It is well known in the literature that as the level of complexity increases, the risks and costs associated with the well tend to be higher. In the last decade, exploration companies have tried to quantify these wells' technical and geological complexity as a function of data and model reliability and availability (Nzeda, 2014; Milkov, 2014). An example is the operator Wintershall who developed the Drilling Complexity Index (DCI), creating a method to estimate the complexity and therefore account for potential budget and time overruns in a point system (Nzeda, 2014). However, the DCI does not provide the ability to determine the planned POS for performance and well cost. The authors of the DCI method analyzed data from 21,000 wells drilled worldwide between 2008 and 2012. Based on their analysis, there is a strong correlation between the number of casing strings (sections-to-be-drilled) of the well and the DCI. A well with 4 to 5 casing strings is considered a Medium DCI and has an associated cost per meter up to $10,000 USD, while those with more than five casing strings are considered to have a High DCI (usually high-pressure wells); these have an estimated cost per meter up to $16,000 USD. A similar correlation was found between the well complexity , its drilling performance (expressed in days/1000 m), and the well cost (cost per meter drilled). The authors of the DCI determined that the drilling performance for an offshore High DCI well is 18.82 days per 1000m, while for a Low DCI well, it is estimated at around 4.63 days per 1,000m. This represents an increase of 14.19 days (per 1,000m) or a 306% increase in the estimated time. Intuitively, the same principle of increased well complexity would similarly significantly affect the Probability of Success (POS) determination of the entire well delivery process. However, no known and published data in the industry literature supports the claim to date. Thus, using the methodology and tool provided in this research paper, it is important to better understand the complexity, risks/opportunities, and POS associated with each stage of the drilling process. This will be referred to hereinafter as O&G POS Well Delivery Process.

In the oil and gas industry, POS is normally associated with geological POS, meaning the chances of making a discovery. This estimation is a portion of the well technical and economic assessment, and it is critical for the well to enter the portfolio of investment, referred to by the authors of this study as the POS decision to drill. However, little is known about how this probability is affected by engineering or drilling decisions made later in the process, and how these can be evaluated as risks or opportunities. This raises the importance of measuring the POS in a way embedded throughout the well-delivery process.

In summary, Oil and Gas (O&G) wells drilling is risky and expensive. The cost of drilling is typically underestimated, and there is little understanding of the certainty or Probability of Success (POS) of achieving the well objectives within the estimated cost. This dissertation presents, for the first time, a publicly available POS Cost method/tool that enables O&G operators to estimate the cost of well drilling substantially more accurately and improve the POS of accomplishing the drilling for the estimated cost. This POS Cost method employs a comprehensive, expert-based assessment of risks and risk mitigations that are incorporated into a Monte-Carlo-based simulation of the well drilling process.

Results for applying the POS Cost method/tool to a sample well drilling operation demonstrated that, without employing a risk assessment/risk mitigation approach, the POS Cost of the sample well was roughly 40%, but with the risk assessment/risk mitigation included the POS could be increased to over 80% for an additional cost of roughly 4% for the risk mitigation. Many O&G operators would gladly trade that additional cost for risk mitigation to obtain an 80% POS or greater for accomplishing the well for the estimated cost. This enhances the assurance for the Approval of Expenditures (AFE) and increases the likelihood of successfully achieving the objectives of the well while accounting for time efficiencies due to the incorporations of the mitigation strategies. The POS Cost Tool can also be used to create and evaluate best value options for problem-solving during the drilling process to improve POS for the remainder of the operation.

1.2 Research Questions

The proposed hypothesis is that we can develop a method for determining the POS of accomplishing the well design and execution for a specified cost or schedule to allow key decision makers to determine whether and how to proceed, and to enable improved POS of completing the well during execution. This research focuses only on the POS for the cost associated with the planning for the early stages of the well delivery process and illustrates how the use of risk/opportunity mitigations strategies can produce acceptable POS for Cost that can be managed from the project inception and throughout its completion.

1.3 Research Contributions

Probability of success (POS) has several significant contributions in the fields of investment, performance measurement, uncertainty management, asset utilization, risk quantification, and communication of project risks' impact on an economic metric.

Specifically of interest, incorporating POS into the well delivery process is a game changer for decision-makers as it provides an added measure for a given investment level for the best technical and economical estimate. This allows decision-makers to better understand the potential risks and returns associated with their investments and make more informed decisions in a timely manner.

Furthermore, the probability of success offers an improved approach to performance measurement and uncertainty management during operations. It helps companies better assess their assets' performance and manage uncertainty related to production, operations, and maintenance. Thus, POS provides a new means for the optimization of asset utilization, new technologies, and mitigation strategies.

In summary, POS is a novel approach to quantify, manage, and communicate project risks' impact on an additional economic metric (complementary to NPV, ROI, etc.). This enables companies to better understand project risks' impact on their financial performance and communicate these risks more effectively to stakeholders. While there are currently no publicly available tools unique to the oil and gas industry, the probability of success can offer significant benefits to a wide range of sectors beyond oil and gas.

1.4 Organization

This dissertation is organized as follows:

Chapter 2, presents a paper entitled "Probability of Success: What is it? and How can it be used to Improve Risk, Opportunity, and Cost Assurance?" which is mainly focused on laying out, step by step, the method for estimating the POS for Cost and determining the risk and opportunity factors and mitigation profiles for the well life cycle. Thus, this paper includes risk and opportunity identification based on a comprehensive literature survey, and risks and opportunity profiles based on the industry experience from a subject matter experts panel.

In Chapter 3, a paper entitled “Enhancing Probabilistic Drilling Cost Estimations with Risk and Opportunity Management” is presented. In this study, the authors show the detailed mechanics of applying the POS cost methodology to illustrate how the process works on a sample case. The sample risk and opportunity factors (derived in the paper presented in Chapter 3) for different stages of the well-drilling life cycle are input into the commercially available Crystal Ball Monte Carlo Software tool to determine the estimated POS of achieving the project cost. The study compares the implications of incorporating mitigation strategies into the POS estimations for total well cost.

Chapter 4 consists of potential future research areas.

1.5 Methodology

Given the nature of the study, a multidisciplinary and cross-functional approach was taken as the method selected and proposed for this research. The main objective was to develop a methodology and POS tool that would enable a visual means for decision-makers to strategically determine the most viable options based on the well objectives using simple but robust risk and opportunity assessment that can improve the project's probability of success. Note that there is no currently known tool in the industry with such capabilities, at least publicly available. This was accomplished in two technical publications. These two publications intended to (1) describe a step-by-step method for estimating the POS for achieving Project Cost (which can be modified and applied to all stages of the well-drilling cycle) and (2) illustrate the application of the POS method for a sample well. The methodology and key steps are presented in Figure 1-2 in a flowchart format illustrating the order and relationship of the steps. Figure 1-2 also describes which steps were covered in this first publication and addressed in the second paper.

The first paper focused on introducing the audience to the nature of the problem, laying out the basis for POS estimations, and establishing the primary risk and opportunity factors, and their associated cost values with and without a mitigation budget to be included in the Baseline Project Plan. These risks and opportunity factors are based on extensive research and industry experience. The actual list of risk and opportunity factors and their respective values with and without mitigation may be highly proprietary and will differ depending on the complexity and application of the project. Thus, the factors and values provided in the first publication were based on generally available open literature information. The goal was to develop the necessary inputs to prove the value of the methodology, without the intent of being prescriptive.

The second publication describes the detailed mechanics of applying the POS cost methodology to illustrate how the methodology works on a sample well case for both the program planning and program execution phases. The sample risk and opportunity factors derived in the previous publication for different stages of the well drilling life cycle become the input into the commercially available Crystal Ball Monte Carlo Software tool to determine the estimated POS of achieving the project cost (Expected Monetary Value). Note that, although POS can be performed for multiple stages and factors (i.e., cost, schedule, and performance) for this work only POS cost will be addressed. The methodology provided can be adapted for multiple applications (performance and schedule) in future work.

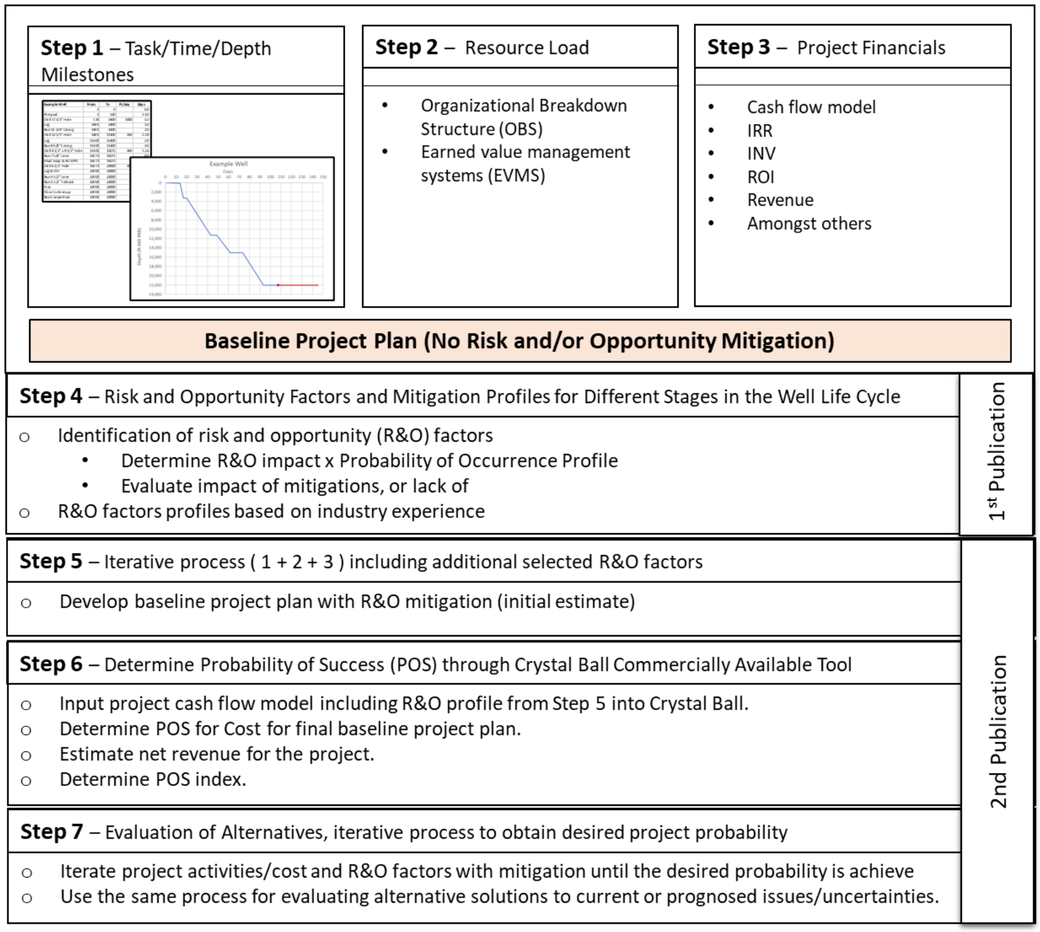

Figure 1-2: Steps to Develop and Implement POS Cost to Create and Manage a Well Drilling Project

At the conclusion of this research work, the goal was to provide a method/tool that any project team could continually use the POS method to evaluate alternatives for project problem solving using the risk/opportunity mitigations planned in the initial baseline project plan or by modifying the project plans with other approaches. Thus, the authors assume steps 1 through 3 (see Figure 2) are already in place for this work. The scope of this technical work includes activities corresponding to steps 4 through 7.

The steps presented below represent the proposed method to complete this research.

- Step 1. Perform a literature review to assess current practices in the Oil and Gas industry, specifically in risk and opportunity assessment practices to standardize the critical factors that should be considered at different stages of the process as part of the risk and opportunity process. The main goal is to compile a set of factors and subsequently group them into representative areas, categorized by the user in low, medium, or high risk, and then incorporated into the weighted criteria for well-design selection. This was sustained by empirical data collected from publicly available data.
- Step 2. Perform a literature review to assess current practices in the Oil and Gas industry and other industries, specifically in determining the probability of success practices to standardize the POS tool's methodology, inputs/outputs, and functional requirements. For this, technical experts in the field were critical for data collection. Methods such as surveys, interviews, and focus groups were conducted as required throughout the process. An important outcome of the survey was to determine de-risking and risk mitigation parameters to be accounted for in the POS tool based on actual experiences and operational capabilities.
- Step 3. Define a representative sample well and develop initial baseline project plans with risk and opportunities mitigations.
- Step 4. Define stakeholders’ requirements and develop the POS methodology for well design.

- Step 5. Develop the POS tool based on Monte Carlo analysis tools like Crystal Ball or similar analysis.
- Step 6. Conduct a case study application based on a real-world project (sample well).

1.6 Applications and Limitations

The method and risk assessment developed in this dissertation was based on the well-delivery process for implementation on multiple projects and applications. However, the proof of concept was done with an onshore application only. The main difference between applying the method to onshore or offshore applications will be the Baseline Project Plans. The associated cost and resources will be different, and the impact of the risks and mitigations will be different as well, even for similar projects. The risks identified and risk mitigation methods are the same between onshore and offshore applications, but the magnitude of the risk impacts and mitigations will scale differently between the onshore and offshore applications.

This work was mainly performed on the Crystal Ball suite from Oracle, a widely used probabilistic modeling and simulation tool. However, there are some limitations to using this software for modeling the Probability of Success (POS) in the Oil and Gas industry. Some potential limitations include:

Limited data: POS estimates require historical data on exploration and production outcomes, such as the success rates of previous wells. This data, if available, is often considered proprietary and highly confidential. In some cases, limited data may be available, especially for new or exploratory regions or reservoirs. This can make it difficult to accurately model POS using Crystal Ball.

Uncertainty in input variables: POS models for this application rely on input variables such as risk profiles and mitigations specific to each project or application.

However, there is often a high degree of uncertainty associated with these variables, making it difficult to generate accurate POS estimates. Crystal Ball can handle uncertainty, but it may be challenging to determine the probability distributions and correlation structures of input variables. For this, the recommendation is to use a panel of Subject Matter Experts to develop the risk profiles and accurately model the most realistic scenarios.

Assumptions and simplifications: POS models are based on assumptions and simplifications about the technical and economic factors that impact exploration and production outcomes. These assumptions may not always accurately reflect the complex reality of the industry, leading to potentially biased or inaccurate POS estimates. Furthermore, changes in these assumptions required the tool to be re-run, this is mainly to the fact that every Monte Carlo simulation run will generate a new set of outputs (iterative process) that will overwrite the previous analysis.

Difficulty in integrating with other software: The oil and gas industry uses a variety of software applications for exploration and production activities, and integrating these with Crystal Ball can be challenging. This can make it difficult to use Crystal Ball with other tools and data sources, limiting its usefulness in some contexts.

Chapter 2

Probability of Success: What is it? and How can it be used to Improve Risk, Opportunity, and Cost Assurance?

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Abstract

The planning associated with drilling and delivering wells becomes key to successfully achieving the well's strategic and technical objectives. These objectives include managing costs, schedules, risk/opportunity, and performance requirements of the asset. Actual performance compared to the planned goals has been often overlooked. Current industry efforts to optimize the use of resources create the opportunity to improve current well-delivery programs by incorporating a robust method for determining the Probability of Success (POS). This POS can be explored at multiple stages of the well delivery process including but not limited to: (1) when deciding to drill, (2) for the as-planned drilling operation, and (3) when selecting and implementing fixes as the actual operation. POS for each of these, can be performed based on either Cost, Schedule, or Performance. Therefore, a comprehensive analysis of the POS for each aspect must be performed independently. Some companies have sophisticated methods for doing this, but they tend to be proprietary and not publicly available. This research focuses only on the POS for the cost associated with planning the early stages of the well delivery process. It illustrates how using risk/opportunity mitigation strategies can produce acceptable POS for Cost that can be managed from the project inception and throughout its completion. This proposed methodology assumes the site assessment has been performed previously indicating a high probability of oil or gas present at the site.

This paper is focused on laying out, step by step, the method for estimating the POS for Cost and determining the risk and opportunity factors and mitigation profiles for the well life cycle. Thus, this paper includes risk and opportunity identification based on a comprehensive literature survey, and risks and opportunity profiles based on industry experience.

1. Introduction and Problem Statement

Exploratory wells are vital to the Oil and Gas industry since they lead to the discovery of unproven and higher-risk unconventional reservoirs. These wells are unpredictable by nature and information about the fields is limited or, in some cases, non-existent; this makes uncertainty a big challenge for these wells' discovery, development, and production. Uncertainty can be due to multiple factors such as geographic/geological location, tight drilling margins, high-pressure/high-temperature High (HPHT) reservoirs, and state-of-art drilling technology. For these reasons, challenging wells tend to have increased operational costs due to non-productive time (NPT) and operational problems due to the nature of the wells.

It is well known in the literature that as the level of complexity increases, the risks and costs associated with the well tend to be higher. It has been found that a significant percentage of the wells attempted in megaproject cost ranges did not achieve their planned initial financial and technical objectives. Delays and budget overruns are commonly seen in these projects and are usually associated with their complexity and managing uncertainty and risks. Thus, it is important to better understand the complexity, risks/opportunities, and Probability of Success (POS) associated with the different stages of the drilling process by using the methodology and tools provided in this research.

The normal lifecycle of an exploration well spans from 2 to 5 years, and in some cases, the wells do not achieve the initial financial and technical objectives. The key challenge remains how to compare and select the best potential options and increase the chances of successfully completing the wells, making them feasible from an investment standpoint. It is critical for the continual evolution within the industry, to determine a method to successfully de-risk all the potential well designs and select the ones that will enable achieving the well objectives while remaining economically and technically feasible. At the same time assess the POS for completing the well within the required cost and schedule for the well design and well real-time drilling process.

This becomes a game changer for well selections and assessments, it enables decision-makers to evaluate a single metric for POS for a given investment level. This process will incorporate both risk/opportunities and potential mitigations in a single metric that may represent the relationship between cost, schedule, risk, and performance and how each of these can impact the probability of success of a given project. In addition to that, this is a unique industry solution, with potential commercial capabilities in the long term. Based on preliminary research, private or commercially available tools are currently available to provide the POS capability.

2. Methodology

During the first stage of the well life cycle, a comprehensive estimate of the Probability of Success (POS) for achieving the estimated project cost must be provided to management to determine the best value alternatives to the well strategy. Nowadays, many companies implement POS for achieving the Estimated Project Cost. A common practice to POS for Cost estimations includes either schedule or performance requirements being fixed. In an ideal scenario, this estimate of POS for Cost must ultimately include the impacts of risks and opportunities associated with each stage of the project and its associated mitigations. These are also called Baseline Project Plans. Once the Baseline Project Plan for the well has been authorized (Figure 1-1, Stage 2, and forward), the project team could continually use the POS method to evaluate alternatives for solving problems as the project progresses. Using the risk/opportunity mitigation budgets planned in the Baseline Project Plan or modifying the project plans with other approaches. This allows upper management to show the estimated POS's status for achieving the project's planned cost as problems or uncertainties are encountered, alternative fixes are evaluated and implemented. Thus, the POS of achieving Project Cost (Expected Monetary Value) could become a very powerful management tool in successfully planning and executing the well drilling program.

As described by Milkov (2014), the Expected Monetary Value (EMV) of the project is a function of the project's net present value, the POS, and the cost of the project (exploration cost), and is depicted in the equation below:

$$\text{EMW} = \text{NPV x POS} - (\text{Exploration Cost})\text{ x }(1 - \text{POS}) \qquad (1)$$

The wells with the highest EMW will be the projects that best fit the financial and strategic goals in the company's portfolio. This research study assumes that the initial baseline project plans (schedule, cost, and resources) for the well drilling program are in place (Figure 1, Phase 2, and forward). This paper aims to describe a step-by-step method for estimating the POS for achieving Project Cost, which can be modified and applied to all stages of the well-drilling life cycle, in addition to illustrating the application of the POS method for a sample well.

The paper is focused on introducing the audience to the nature of the problem, laying out the basis for POS estimations, and establishing the primary risk and opportunity factors. Their associated cost values with and without a mitigation budget are to be included in the Baseline Project Plan. These risks and opportunity factors are based on extensive research and industry experience. The list of risk and opportunity factors and their respective values with and without mitigation may be highly proprietary. It will differ depending on the complexity and application of the project. Thus, the factors and values provided in this paper are based on available open literature and technical public information.

The authors acknowledge that risks and opportunities will vary from project to project and must be evaluated on a project-specific basis. This paper intends to develop the necessary inputs to prove the value of the methodology, without the intent of being prescriptive. Additionally, although POS can be performed for multiple stages and factors (i.e., cost, schedule, and performance) for the effects of this work, only POS cost was addressed. In future work, the methodology can be adapted for multiple applications (POS for schedule and performance).

3. Literature Survey (definitions, existing solutions, and shortfalls)

Exploratory wells are vital to the Oil and Gas industry. These lead to the discovery of unproven, higher-risk, and high-reward unconventional reservoirs. However, these wells are becoming more complex, especially Deepwater high-pressure and high-temperature wells that present additional challenges. These wells are unpredictable by nature and with limited information about the fields, and in cases non-existent, this makes uncertainty a big challenge for the discovery and development of these wells. Uncertainty can be due to multiple factors such as geographic/geological location, tight drilling margins, high-pressure/high-temperature High (HPHT) reservoirs, and state-of-the-art drilling technology. While uncertainty is commonly related to opportunities or risks for the desired outcome, risks tend to have a negative connotation and are often associated with undesirable outcomes.

As of today, there is no universally accepted definition of risk. Definitions of risks and opportunities and their associated terminology have several variations across different industries and applications. For this paper, the following are used:

Probability of success (POS) - is defined as the likelihood of achieving the well objectives within one or more of the following three main variables: Performance, Schedule, and Cost.

Risk – Risks are uncertainties, which, if they occur, could have both a negative (threat, problems) or positive (opportunity) that could affect the project's ability to meet its objectives in terms of cost, performance, and schedule (probability of success). It refers to a variable with a discreet success or failure outcome for each interval to be drilled (Milkov, 2014).

Opportunity – Positive impact or enhancement that could improve the project's ability to meet its objectives in terms of cost, performance, and schedule (probability of success). For projects, there are at least three categories of opportunity. The first relates to choices made concerning project specifications for the expected project deliverable. The second type of opportunity for projects deals with planning decisions for the work, generally involving trade-offs. The third type of opportunity involves potentially beneficial uncertainties inherent to the project (Kendrick, T., 2015).

Uncertainty – refers to variables, the value of which we do not know, and will not know until sometime in the future (or ever if uncertainty is irreducible). Uncertainty describes the well-related parameters that may be present in the drilled sections (Milkov, 2015).

Acceptable/tolerable risk – the level of risk (minimum risk) that the person or entity is willing to accept /tolerate for the potential of an incident of the estimated nature, frequency, and severity (Christensen, 2001).

Risk Assessment – An analysis that addresses both the probability of a hazards-related incident occurring and the expected severity of harm or damage that may result (Christensen, 2001).

Risk Mitigation –is a strategic risk response wherein a project team takes active steps to reduce the probability or impact of a negative risk to a project. It implies reducing an adverse risk's probability and impact within acceptable threshold limits (Project Management Book of Knowledge, fifth edition).

Risk and opportunity management encompasses the continuous and proactive process of assessing a project's risks and opportunities, developing plans for potential actions, and monitoring and controlling those plans to ensure all project (well and strategic) objectives are achieved and opportunities are fully maximized. This process improves the probability of project success.

Risk assessments have long been the default method for managing uncertainty and project variability in the O&G industry (Suda et al., 2015; Milkov, 2015; Nzeda, 2014; Christensen, 2001). Some of the most widely used methods include, but are not limited to, Hazard Identification Analysis (HazID), Hazard Operability Analysis (HazOP), and Failure Mode and Effect Analysis (FMECA), amongst others. These risk management techniques are usually implemented across different stages of the Well Delivery Process for safety and environmental risk management. However, no known published literature exists that an unbiased risk-based integrated approach can be applied to determine each option's overall risk exposure profile. The key challenge remains how to compare and select the best potential options, make the most educated decisions during drilling operations, and increase the chances of completing the wells successfully, making them feasible from an investment standpoint.

The current approach to decision-making is based primarily on quantified financial results in the form of deterministic values or probability distributions. Nonetheless, even when the risk factors have been identified, as stated, and highlighted by Milkov (2014), there is still significant disagreement in the industry on two main issues. The first one refers to how many risk factors are truly independent of each other and which ones should be multiplied, and secondly, how to estimate the probability for each risk factor. As stated before, there is little published information on exactly how the probabilities of occurrence are defined for each independent risk factor and how they get incorporated into the POS. This is mainly because the assignment of probabilities to individual risk factors is primarily based on the subjective expert opinion of one expert later modified by the subjective opinions of other experts and managers.

All wells have different degrees of severity and types of problems. Managing drilling risks and uncertainty by de-risking by implementing a set of possible viable alternatives can become a game-changer for well assessment and development. Knowing what risks are prone to happen and the likelihood of occurrence helps reduce the impact of potential surprises to a minimum. Thus, enabling a strategic risk assessment and tolerance framework provides the ability to make key decisions early with relatively minimal data while evaluating several options based on different levels of uncertainty. These technologies, however, are costly and challenging. A risk-based integrated analysis system is the initial step to fully investigating the probability of success of the various well design profiles.

A quantitative approach enabled the risk associated with uncertainties in the different profiles to be compared on a common basis for a baseline design. This provides flexibility in the design of the wells to cover a range of likely scenarios based on operational uncertainties. While literature indicates that there are several methods used in the industry for risk identification and mitigation and that there is a significant time and effort dedicated to attempting de-risking the projects, until now, there has not been a consistent, commonly accepted method that embeds and compares the Probability of Success (POS) of actually completing these wells (or well configurations) based on risk, opportunity and cost assessment to enable the selection and subsequently implementation of the most valuable options.

The main purpose of risk assessments on exploratory drilling was to evaluate the well conditions and identify any potential hazards that can occur due to changing conditions and manage them by setting contingency plans. These assessments are continual throughout the project life cycle, and it compromises the use of software tools and personnel with the technical background to interpret and provide solutions that will aid decision-makers to avoid drilling problems generated by these potential hazards. Decisions made at different stages during the well life cycle will significantly differ in the time and information available to make the decision. In the early stages, the decisions can be made in months, while during operations depending on the severity of the risks and probability of occurrence may require decisions to be made in a manner of hours or event immediately (Aldred, et al., 1999). Thus, decision-making during drilling operations to tackle or manage these risks is complex due to all the variables and factors involved.

As a part of the decision-making process, multiple factors are considered. In the first place the risks related to the process, and secondly the probability of completing the project successfully within a particular budget, performance, and timeframe. For the first, the previous sections discussed risks and uncertainty significantly. The probability of successfully achieving a project within its program plans could also be determined as one comparable metric, Probability of Success (POS). Cost, schedule, performance, and risk variables are all factored into this integrated metric. Determining the POS becomes critical for identifying potential risks and opportunities for successfully reaching the project objectives. Therefore, POS is defined in this paper as the likelihood of achieving the well objectives within the following three main variables: Performance, Schedule, and Cost. For large and complex drilling programs it is even often beneficial to determine the POS for successfully achieving each stage in the well delivery program process including (1) when deciding to drill, (2) for the whole as-planned drilling operation, and (3) when selecting and implementing fixes as the actual well delivery operation is conducted, which requires selecting and implementing alternatives to deal with problems encountered as they occur.

Historically, a few methods have been used for evaluating the POS as a measure of expected value. It is common to use statistical distributions, such as, binomial, and normal, which have also been used for describing the occurrences of successful or unsuccessful trials. Another widely used method is decision trees with associated probabilities. These are considerably robust for obtaining the expected values, and it has been applied for decision-making amongst various prospective wells or projects. Some of the most sophisticated O&G companies use statistic-based analysis tools that convey the correlation between the probability and the expected value for key parameters (Murtha, 1997).

Some standard tools are Monte Carlo Simulations or Crystal Ball commercial software applications. The Project Management Book of Knowledge defines Monte Carlo Simulation as a technique that computes and iterates project cost or schedule many times using inputs values selected from probability distributions of possible costs and durations, to calculate a distribution of possible total project cost or completion dates (Project Management Book of Knowledge, fifth edition). These tools do not make decisions, analyze the data, or provide recommendations. Thus, it’s long known that these tools can be insufficient to effectively estimate and control project cost, given the lack of tools to accurately measure the probability and more importantly uncertainty leading to suboptimal outcomes because of poor decision quality (Newman 2018). This lack of flexibility to identify the probability of cost overruns and schedule delays was highlighted over 20 years ago by Westney (2001) and continues to present challenges to operators and service providers. With this backdrop, it may be challenging to identify and implement projects that could deliver competitive shareholder value.

This echoes the necessity of a robust tool and method for determining and increasing the Probability of Success (POS) in achieving the planned costs. To prove the proposed POS methodology, it is necessary to develop:

a. Risk and opportunities profiles and mitigations

b. Baseline project plans

To address the first portion, it is necessary to identify the risks and opportunities profiles specific to the Oil and Gas industry, and of the importance of this research, those with a potential impact on the POS cost. For that reason, the following sections will present an overview of risk and opportunities assessment in the well delivery process, the identification of the risk and opportunity factors and their mitigations, and the profiles that will be an input for the POS methodology.

4. Risk and Opportunity Assessments in the Well Delivery Process Overview

Risk and uncertainty analysis and management are a traditional yet still-evolving trend in project cost and schedule estimations. Best practices include the early identification of risks and associated uncertainty and their monitoring throughout the project life cycle. Risks and opportunities are identified in the early project stages, from the planning phases involving feasibility, concept development, strategy evaluation, and pre-engineering.

However, risk management is a controversial issue, the organizational and technological complexity of these wells generate unique risks. Probability assessments are expert knowledge dependent. Consequently, project managers must rely on the results of subjective probabilities (Kassem et. all, 2020). To date, there are insufficient tools to properly conduct these analyses that carry out throughout the project lifecycle and maintain consistency in the study, or in some cases, incorrectly used of the same, which leads to a false sense of security shattered by the loss of objectives and time/cost overruns (Peterson, et. all, 2005). Although current technology like machine learning has been tested to emulate experts' judgments there are still challenges and limitations, mainly based on a lack of contextual and environmental information, which still requires judgments that have been elicited using formal judgment elicitation methods (Brito et. al, 2022). The lack of data from actual applications leads to significant sets of assumptions and simulation work required for their development (Zhou et. al, 2017; Khakzad, 2015). Thus, to this date, probabilistic risk assessment relies on experts' judgments.

Risk management is a systematic process that is traditionally divided into three main activities:

- Risk and Opportunity identification - determine which risks that might affect the project and register their characteristics.
- Risk and opportunity evaluation – analyzes the likelihood and impact of each, and prioritizes based on project objectives, and company policies.
- Risk and opportunity control – set mitigations to treat or respond to the risks conditions, monitor the results, and adjust as necessary.

Risk management also includes the process of opportunity management (opportunity assessment and mitigation). It presents opportunities to identify new technologies that add value and maximize profit. With sufficient knowledge and information for the project execution, the project team's understanding, and communication of the uncertainty in the risk management process, there is also an opportunity for reducing activities durations and using proven software and methods in place. The framework illustrated in Figure 2-1 will be implemented for this analysis. This study was heavily based on a literature review and critical experts' judgment. The scope of the study research was limited to articles between 2000 and 2021.

This scope included state of art on risk factors and their impact on oil and gas project success, including cost and time overruns. A total of 40 articles, conference proceedings, technical reports, and sources of publicly available information were retrieved. According to the proposed methodology, the first step is to gather all potential risks. Subsequently, the study provides a general classification of the risk group by listing several sub-risks and allowing the possibility of the inclusion of the new classifications under major groups to prioritize those risks and evaluate possible opportunities.

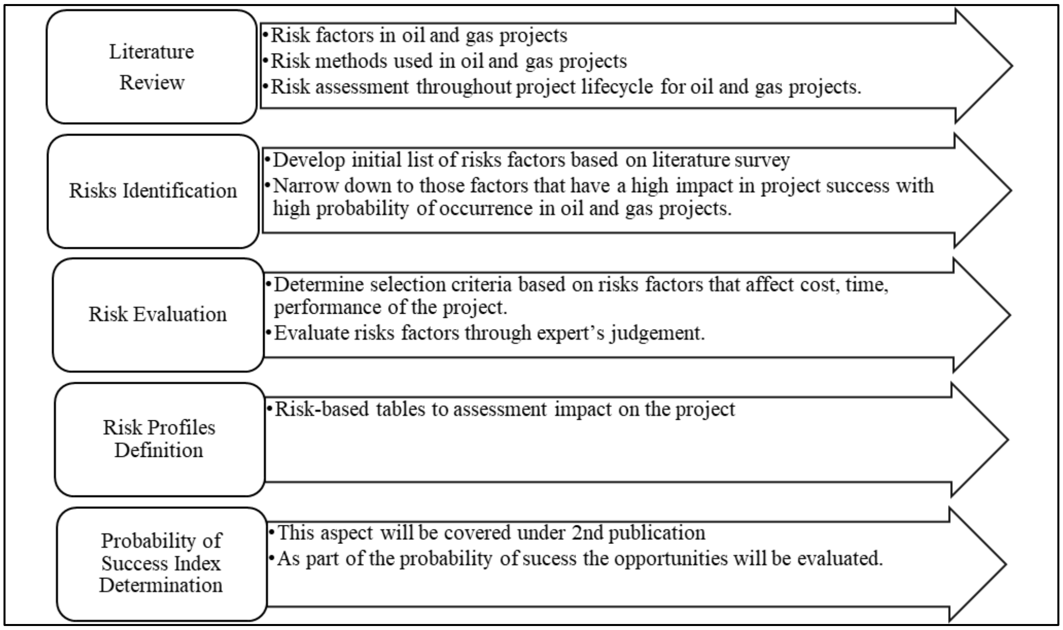

Figure 2-1: Framework Used for Risk-Based POS Analysis

5. Risk-based Probability of Success Analysis

Identification of Risk and Opportunity Factors

Nowadays, there are a vast number of techniques for risk identification where traceable data is limited, some typical applications include brainstorming workshops, questionnaires, interviews, and surveying panel experts' methods, such as Delphi, or nominal group technique (NGT) (Mojtahedi et al, 2010). However, these analyses heavily rely on specific knowledge, experience, expert judgment, and the rules of thumb to structure and facilitate a risk assessment. This leads to a lack of detailed identification, analysis, and summarization of all risk-associated oil and gas exploration projects. In most cases, they fail to consider the time-dependent impacts of these risks factors in the project lifecycle (Li et. al, 2020).

Literature shows that the four significant effects of risk factors in oil and gas exploration wells are related to:

- Time overruns
- Cost overruns
- Failure to achieve project objectives (Performance)
- Project cessation

Accurately estimating risks, specifically those with an impact on schedule and cost requires evaluating uncertainty at different levels for strategic decision-making. Both opportunities and threat define uncertainty in a project context and are inherent to risks. Thus, uncertainty can be managed similarly to an industry's known risk assessment processes. The primary sources of uncertainty and sources of risk factors have been classified by previous authors (Chamanski et. al, 2002; Gu et. al, 2012; Li et. all, 2020; Kassem et. al, 2020), and will be broadly explored as technical, commercial/economic, and management/project management.

Previous researchers have conducted comprehensive analyses and adopted weight risk factors to prioritize analyzing oil and gas resource development, however, the inherent relationship between risk and benefit should have been discussed in detail (Lie et. al, 2017a). In later publications Lie et. al (2017b) clarifies that the risk level varies according to the difficulty and type of exploitation and the quality of oil and gas, thereby influencing the decision-making.

For this study the scope of the risk identification will focus on those associated with project stage gates (see Figure 1-1) from 1 (assumes as already completed) to 4, which include the following 1) feasibility and concept design, 2) front end detailed engineering, and 3) operations and project management related risks factors. Figure 2-2, emphasizes these stages and shows an example of some of the main activities conducted in these stages. This example is specifically related to this application, the stage gates and activities will vary depending on specific applications, and the purpose of the analysis.

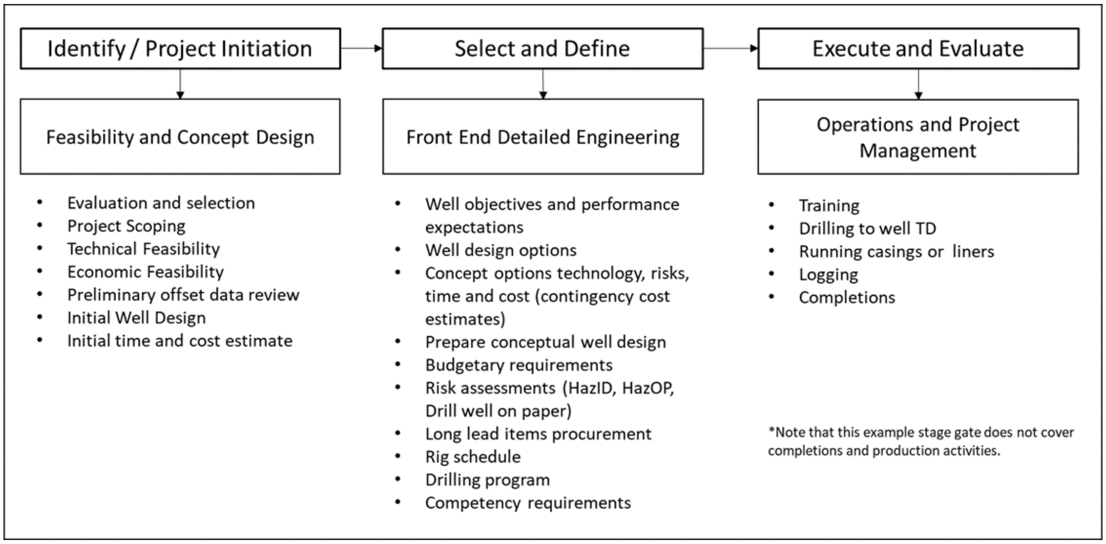

Figure 2-2: Stages to be considered on Risk and Opportunity Assessment

The main reasons associated with this decision are summarized below:

- In the early stages (2) there is a wide accuracy for determining major schedule and cost impact. The initial budget has already been allocated for the project, and the project has been included as part of the investment portfolio. By the time state (3) is reached there is the tightest accuracy from the design of the well to the definition of the execution.
- Risk assessments in these areas are conducted individually, at multiple stages. Thus, tend to be subjective to the subject matter experts' experience and judgment, and may vary from stage to stage depending on changes in scope, or resource commitments. A detailed list of shared risks, opportunities, and mitigations can be developed.

- Risk acceptance and well success criteria have been defined or can be optimized with a consistent risk-based approach.
- There is no time-dependent risk-based analysis that can be measured throughout these stages and directly correlated to a probability of success for the well or project.
- Project performance will be significantly affected by these decisions made during these stages. The types of uncertainties present in these stages are tied to risks that may or may not have been identified in the early value identification phase and may or may not have an impact on the project performance. Understanding the origins of these uncertainties play a key role in making informed drilling decisions.
- The feasibility study and design preparation for the project is considered a crucial stage during the project's life cycle and may consider a source of risks that later affects the execution of the project or increase the cost.

This approach will ensure the definition of risks and opportunities associated with the uncertainty during feasibility study and design, and execution (detailed engineering, and construction). For risks and opportunities identification, the data collection and preparation consisted of the findings from the literature survey (see Table 1), Delphi method and brainstorming, systematization and definition of possible project execution, and operational risks and opportunities. The author collected information about publicly available case studies and gained preliminary qualitative knowledge of the categorization of the risks and opportunities influencing the probability of success of the exploration projects. The final sample consisted of 30 significant risks/opportunity factors, clustered into the following risk and opportunities categories:

- Feasibility and Concept Design-related risks factors (planning).

- Front-end detailed engineering-related risk factors (implementation).
- Project management-related risk factors.

After identifying the major categories, from the available literature and based on experts' judgments the authors classified and ranked the risks and opportunities factors that may have a higher correlation with the probability of success indicators (cost, schedule, and performance). Following the identification process, the authors gathered to systemize the data, created a cleaned-up list of the most relevant categories, and clustered the data into three main groups. To summarize high-level findings from the comprehensive literature survey the most significant risk identification categories are presented in Table 2-1.

Table 2-1: Example Case - Preliminary identification and classification of risks factors based on literature survey.

Risk Stage Type	Risk/Opportunity Factors	Relevant Literature Survey
Feasibility-study and design related (9)	• Resource characteristics (depth, oil/gas content, permeability) • Improper project feasibility (Type of well, Casing Design) • Lack of data accuracy and survey information • Unreliable data • Frequent design changes • Delay in decision making • Improper project planning and budgeting • Lack of detailed items • Inadequate tendering	Kassem, M. A., Khoiry, M. A., & Hamzah, N. (2020). Kassem, M. A., Khoiry, M. A., & Hamzah, N. (2019). Li, Z. X., Liu, J. Y., Luo, D. K., & Wang, J. J. (2020). Zoufa and Ochiend (2011) Nzeda, B. G., & Schamp, J. H. (2014) Gu, M., & Gudmestad, O. T. (2012)
Front end detailed engineering. (12)	• Type of Well (exploration, appraisal, development, offshore, HPHT, etc) • Pressure and temperature (drilling margin, high pressure/high temperature, overbalance requirements, mud weight and equivalent mud weight management) • Casing program (number of strings, critical setting depths, etc.) • Formation issues (stability, multiple zones, etc.) • Well trajectory (TVD, MD, max inclination, doglegs, etc) • Exploration technology (new, proven) • Drilling and completion technology (new, proven) • Rig characteristics (rig type, water depth, capability, modifications, operability, track record) • Field experience and history (drilling problems, stuck pipe, drill string failures) • Fracturing technology • Unforeseen circumstances • HSE considerations (location, H2S, CO2, discharge, etc.)	Kassem, M. A., Khoiry, M. A., & Hamzah, N. (2019). Li, Z. X., Liu, J. Y., Luo, D. K., & Wang, J. J. (2020). Nzeda, B. G., & Schamp, J. H. (2014) Aldred, W., Plumb, D., Bradford, I., Cook, J., Gholkar, V., Cousins, L., ... & Tucker, D. (1999). Westney, R. E. (2001).
Operations and Project management related risks factors (9)	• Organizational capacity (management systems, decision-making mechanism) • Lack of strategic project planning results • Poor Planning and controlling for Scheduling, and Budgeting • Execution errors • Delays on approval • Environmental and politically sensible region • Poor contract management • Logistic and set-up	Kassem, M. A., Khoiry, M. A., & Hamzah, N. (2020). Kassem, M. A., Khoiry, M. A., & Hamzah, N. (2019). Li, Z. X., Liu, J. Y., Luo, D. K., & Wang, J. J. (2020). Aldred, W., Plumb, D., Bradford, I., Cook, J., Gholkar, V., Cousins, L., ... & Tucker, D. (1999).

Risk and Opportunity Factors Selection

The authors of this work understand that the risks and opportunity assessment is highly dependent on the specific project and requirements. The intention of this work is not to produce an exhaustive registry of all possible risks/opportunities than can occur in the industry, but to obtain the required inputs for the risk/opportunities factors profile so that the POS methodology can be proven as an effective method to improve risk, opportunity, and cost assurance in the well delivery process. Thus, the risk and opportunity identification were assessed through a literature survey, and subsequently, a Delphi method was used as a technique for the selection and prioritization of those of most relevance for the POS.

The Delphi method was used to understand the impact of the potential risks and opportunities. This was completed via written questionnaires, interviews, and brainstorming sessions. The main goal was to identify the top ten risks and opportunities that according to the expert panel can significantly impact the cost of the project and its potential mitigations.

Questions were provided to the technical panel of experts that were intended to accomplish the following objectives:

1. Validate the list of risk/opportunity factors identified and discover any missing or additional items that should be considered.

2. Determine the Risk Criteria (RC) for each of the identified 30 risk/opportunity factors.

3. Identify risk mitigation strategies, their potential effectiveness in reducing the risks, and their probability of success after implementation.

For this work, the risks were rated based on a Risk Criteria (RC), which can be defined as the product of the probability of occurrence (PO) of the event happening and the impact (I) if the event happens. Thus, it is given by the following equation:

$$RC = PO \, x \, I \tag{2}$$

The resultant measurable numerical scale (between 3 and 9) was later converted to a Likert descriptive scale in terms of their crucial roles as risks associated with POS cost, and its classification is presented in Table 2-2. Based on the literature, the proposed process and scales have been used in megaprojects and relatively small complex projects. This is presented as an example, when used for a specific organization or project must be adapted to the particular needs of either. This is presented as an example, when used in a particular organization or project must be adapted to the specific needs of the either, including specific monetary value for HSE/Safety injuries, or value of the assets.

Table 2-2: Relative Risk Matrix

		Probability of Occurrence		
		Low (1)	Medium (2)	High (3)
Impact	Low (1)	**1**	**2**	**3**
	Medium (2)	**2**	**4**	**6**
	High (3)	**3**	**6**	**9**

As previously mentioned, to calculate the risk criteria two variables are required to be defined, these are Probability of Occurrence (PO) and Impact (I). The following numerical scales have been selected for this purpose.

- Probability of Occurrence (PO):
  - 1 (rare, unlikely) = Never heard of or not likely to occur in the drilling industry.
  - 2 (possible/likely) = Has occurred in the drilling industry.

- 3 (highly likely) = It is likely to occur in the drilling or is known to have occurred more than once in the industry.

- Impact (I) refers to the impact on the POS evaluated in terms of Health/Safety, Environment, Assets, and Reputation. As provided in the table below:

Table 2-3: Relative Scale for Impact Values Assessments

	HSE (health and Safety)	Environment	Assests	Reputation
Low (1)	No lost time or occupational illness. Low or minimal affect/injury on the person	No or slight effect	No or slight damage	No or slight effect
Medium (2)	Lost time injury or occupational illness (recoverable) Major effect on one person or menor effect on several.	Minor, localized effect	Minor, localized damage	Limited or local effect
High (3)	Fatality; serious injury or occupational illness (non-recoverable)	Major Effect	Major or extensive damage	National or greater effect

Once the risk criteria have been determined, the following two variables are related to the mitigation strategies and their impact. There are 1) Mitigations Probability of success (MPOS) and 2) Risk Mitigation Level (RML), and they are defined as follows:

- Mitigations Probability of success (MPOS) - is defined as the likelihood of achieving the well objectives within one or more of the following three main variables: Performance, Schedule, and Cost, if the proposed mitigation/treatment can successfully solve the potential hazard. This number defines how likely the mitigations in place are to succeed given the possible risk/opportunity occurs.

The numerical scale is based on the following criteria.

- MPOS (1) Low: Mitigations in place have a very low probability of success.
- MPOS (2) Medium: Mitigations in place have a probability of success between 50% and 70%
- MPOS (3) High: Mitigations in place have a probability of success more significant than 70%

- Risk Mitigation Level (RML) corresponds to a strategic risk response in place. A project team takes active steps to reduce the probability or impact of an adverse risk to a project. It implies reducing an adverse risk's probability and impact within acceptable threshold limits. This will be the result of dividing the Risk (values 1 through 9) by the Mitigation Probability of Success (MPOS, values 1 through 3), and it is given by the following equation:

$$RML = RC / MPOS \tag{3}$$

The values for RML ranges from 0.33 through 9. Where the resultant value will imply:

- $RML < 1$ = Low risk remaining after mitigation in place
- $1 \leq RML \leq 2$ = Medium risk remaining after mitigation in place
- $RML > 2$ = High risk remaining after mitigation in place

Once the questionnaire was completed, it was distributed to the panel of experts, made up of 5 individuals with an average year of experience of 34 years in the industry. A high-level summary of each subject matter expert (SME) is presented in Table 2-4. Note that these individuals have worked over a wide range of applications within the industry, including operators, service companies, and consulting firms, which provides considerable knowledge across multiple parties and applications within the industry.

Table 2-4: Summary of Experience from Subject Matter Experts (SME) Surveyed

	Current Position	Years of Experience in Oil and Gas	Areas of Expertise
SME1	Senior Well Engineering Advisor	47	Project Manager / Coordinator Site Manager / supervisor Well Delivery Process Well / Drilling Engineer
SME2	Senior Engineering Advisor	42	Project Manager / Coordinator Site Manager / supervisor Well Delivery Process AFE estimations and Management Well / Drilling Engineer
SME3	Senior Well Engineering Advisor	21	Project Manager / Coordinator Site Manager / supervisor Well Delivery Process AFE estimations and Management Well / Drilling Engineer
SME4	Project Manager	28	Project Manager / Coordinator Site Manager / supervisor
SME5	Project Manager	31	Project Manager / Coordinator Site Manager / supervisor

Although the sample is small, it is considered sufficient to support the depth of the case and industry-oriented analysis conducted. Some researchers have evaluated small samples in the knowledge-based and single-interview-per-participant analyses, among those of relevance:

- Sandelwski (1995) recommends that samples be only large enough to enable the “new and richly textured” understanding of the case under study, but small enough that a deep case-oriented information analysis is not excluded.

- Morse (2015) considers that the more valuable the information obtained from each participant, the fewer participants will be required. The author recommends considering aspects such as scope of the study, nature of the topic, quality of data, amongst others.

6. Results and Discussion

As mentioned before, there were three main objectives for utilizing this method, and the findings based on the experts' opinions are as follow:

The 30 risks/opportunities factors found in the literature are relevant for the evaluation of probability the success, and they can be categorized by either risk, opportunities and in instances both a risk and an opportunity.

As shown in Figure 2-3, results were consistent within the SMEs, regarding the classification of the factors.

All SMEs expressed consensus that the risks associated with the industry are highly dependent and involve different stages and should be included in a Risk Planning process to identify, prioritize, and manage the risk to reach the well and project objectives. Once the risks are identified a response plan should be implemented. Now days, two of the main challenges are related to:

- Lack of time to identify and understand the risks early in the process. There is usually a rush to prepare a cost estimate for an AFE.
- Lack of a multidisciplinary team involved in the development of project plans.

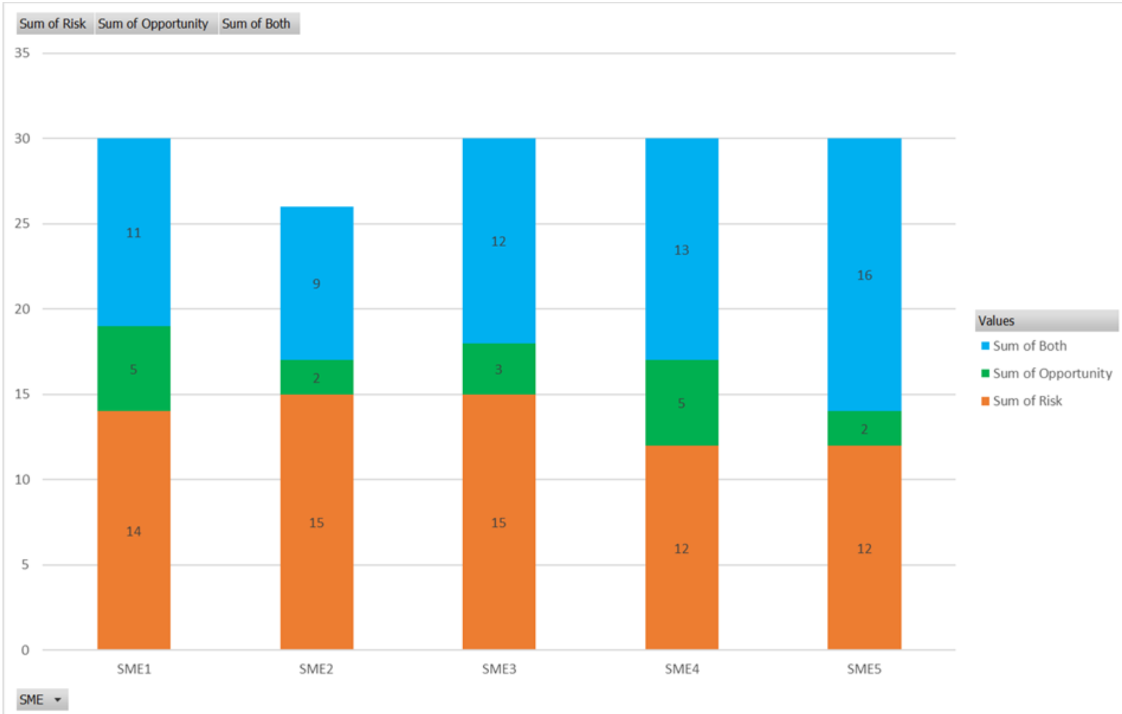

Figure 2-3: Risk/Opportunity Factors Classifications- Individually rated by SMEs

As seen in Figure 2-4, the 30 risks/factors were classified by each SME, by the Risk Criteria proposed (low, medium, high). All these risk/opportunities have been logged into a Risks/Opportunity matrix prior to accounting any mitigation. The SMEs reached a consensus on the final assigned risk criteria value given to each factor. Note that this is a common approach used in the industry. Workshops are typically held where multidisciplinary teams gather to ponder each application's value. However, these are typically done on the advanced stages of the Well Delivery Process, and more technical focus than based on actual project performance or probability of success. As can be seen in Figure 2-5, out of the 30 factors, a total of 7 risk/opportunity factors have been classified as Low, 15 were considered Medium and 8 were considered High.

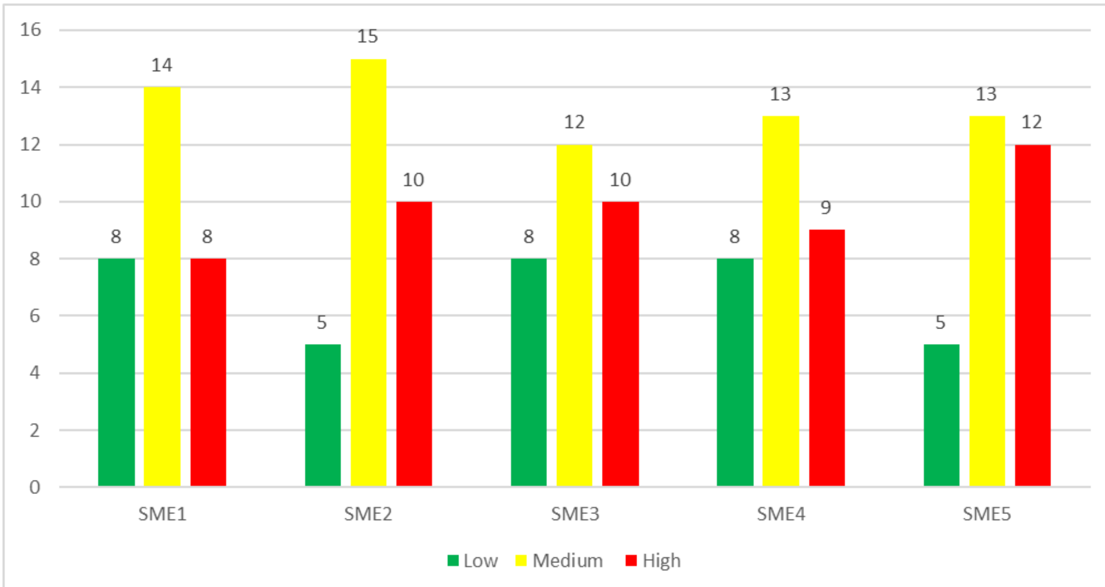

Figure 2-4: Risk Criteria Classifications by SME - Individually Rated

		Probability of Occurrence		
		Low (1)	Medium (2)	High (3)
Impact	Low (1)	**4**	**3**	**2**
	Medium (2)	**2**	**10**	**1**
	High (3)	**1**	**3**	**4**

Figure 2-5: Pre-mitigation Likelihood-Severity

The final step was to identify the possible risk mitigation strategies, their potential level of effectiveness in reducing the risks, and their probability of success after implementation. This would enable the analysis of the most critical factors based on the risk classification post-mitigation. High values for RML will imply that the higher the number, the less likely the planned mitigation/contingency is expected to succeed, the higher the Impact if the mitigation fails, or the higher the Probability of Occurrence that the event will happen.

Table 2-5: Post-Mitigation Likelihood of Success based on MPOS – SMEs Consensus

Mitigation Probability of Success (MPOS)		
Low (1)	Medium (2)	High (3)
Mitigations in place have a very low probability of success	Mitigations in place have a probability of success between 50% and 70%	Mitigations in place have a probability of success greater than 70%
0	**13**	**17**

Table 2-6: Post-Mitigation Likelihood of Success based on RML – SMEs Consensus

Risk Mitigation Level (RML)		
Low Risk Remaining	Medium Risk Remaining	High Risk Remaining
6	**19**	**5**

Table 2-7 presents the top 10 risk and opportunities factors that the panel of experts has identified as critical factors affecting the probability of success in the well delivery process, including its potential mitigations based on experience of the technical experts. This list has been identified as risks and opportunities factors specific to the Oil and Gas industry, and of the importance of this research, those with a potential impact on the POS cost, and those that will be converted into inputs for the POS methodology.

Table 2-7: Top 10 Risk/Opportunity Factors with Associated Mitigations

ID	Risk/Opportunity Factors	Possible Mitigations	Risk Criteria (RC) Pre-Mitigation	Risk Mitigation Level Post-Mitigation	MPOS Post-Mitigation
2	Improper project feasibility (Type of well, Casing Design)	Develop confidence in project data and studies Generate interaction with all project's relevant personnel Evaluate offset data, lessons learned and similar applications	9	3.00	3
5	Frequent design changes	Define well objectives with regards to safety, environment protection, personnel health, operations performance, and data acquisition. Complete design input analysis (e.g., PPFG) prior to developing the basis of design. Develop an agreed basis of design and freeze the document prior to initiating design work. Provide sufficient time for offset well data analysis and well design. Develop decision trees	9	3.00	3
11	Pressure and temperature (drilling margin, high pressure/high temperature, overbalance requirements, mud weight and equivalent mud weight management)	Detailed analysis of offset data, and use of LWD with special tools in exploratory wells Establish PPFG estimate and understand the potential uncertainty. Develop well designed casing programs to safely drill the well and accommodate uncertainties in formation properties. Ensure relevant expertise is applied to the well design: HPHT, drilling fluids, MPD. Perform equipment maintenance prior to drilling challenging intervals. Perform well control drills prior to drilling challenging intervals to confirm quick, effective response. Perform sensitivity analyzes	9	3.00	3
6	Delay in decision making	Plan in advance all possible scenarios and contingency plans Develop project management practices Prepare Management of Change plans Develop decision trees in advance	6	3.00	3
4	Unreliable data	Determine which data is unreliable and ignore. Reacquire data that is unreliable or missing. Implement data QAQC procedures. Use independent measurements to confirm data accuracy. Practice disciplined analysis to ensure the most accurate data characterization. Document and quantify, if possible, the uncertainties in the data. Develop well plans and procedures to accommodate the uncertainties. Risk assesses best case and worst-case scenarios accounting for uncertainty Evaluate different methods for data collection, and mining. Establish multiple check points for data review	6	2.00	2
7	Improper project planning and budgeting	Allow time for planning. Forecast potential outcomes based on historical performance of similar projects Incorporate management reserve based on risks assessments	6	2.00	2
10	Type of Well (exploration, appraisal, development, offshore, HPHT, etc)	Analyze offset data, lessons learned, and recommended practices Develop contingency and operational procedures	6	2.00	2
17	Rig characteristics (rig type, water depth, capability, modifications, operability, track record)	Tender service for drilling contractors 3rd party verification of specifications and requirements Define rig requirements based on well objectives Perform rig surveys, commissioning, and testing of equipment Evaluate rig denomination (ABS, DNV, etc)	6	2.00	2
24	Poor Planning and controlling for Scheduling, and Budgeting	Offset wells data review Define project and well objectives Define timelines for all major activities with inputs from all stakeholders Benchmark against similar wells performance	6	2.00	2
25	Execution errors	Ensure relevant expertise is applied to the well design: HPHT, drilling fluids, MPD. Assign experienced, proven personnel in well supervision and operations leadership positions. Develop crew capability and knowledge of rig operations. Implement a disciplined management of change process to control risks due to unplanned events. Develop clear plans, procedures, and contingency plans. Follow the plan. Develop operational and contingency procedures Risk assesses critical operations Implement management of change process	6	2.00	2

7. Chapter 2 Conclusions

All wells have a different degree and nature of problems associated with each of them. Managing drilling risks and uncertainty by de-risking possible viable alternatives can become a game-changer for well assessment and development.

The probability of successfully achieving a project within its program plans could also be determined as one comparable metric, POS. Cost, schedule, performance, and risk variables are all factored into this integrated metric. POS was defined in this paper as the likelihood of achieving the well objectives within the following three main variables: Performance, Schedule, and Cost. There are two main inputs to prove the proposed POS methodology (1) risk and opportunities profiles and mitigations, and (2) baseline project plans.

While literature indicates that there are several methods used in the industry for risk identification and mitigation, and that there is a significant time and effort dedicated to attempting de-risking the projects, until now, there has not been a consistent, commonly accepted method that embeds and compares the Probability of Success (POS) of actually completing these wells (or well configurations) based on risk, opportunity and cost assessment to enable the selection and subsequently implementation of the most valuable options.

This paper presented, step by step, the method for estimating the POS and determining the risk and opportunity factors and mitigation profiles for specific stages of the well life cycle. Thus, a risk and opportunity identifications were conducted based on a comprehensive literature survey, and risks and opportunity profiles and mitigations were derived based on industry experience.

Risk profiles and mitigations are key inputs for the POS. However, until today, in the Oil and Gas industry probability assessments are highly dependent on experts' knowledge and tend to be specific to each project. Even with advanced technology like machine learning and AI, insufficient data is available to “train” or “calibrate” the existing logarithms.

The authors acknowledge that risks and opportunities will vary from project to project and must be evaluated on a project-specific basis. This paper intends to develop the necessary inputs to prove the value of the methodology, without the intent of being prescriptive. Additionally, although POS can be performed for multiple stages and factors (i.e., cost, schedule, and performance) for the effects of this work, only POS cost will be addressed. The methodology provided can be adapted for multiple applications in future work.

Chapter 3

Enhancing Probabilistic Drilling Cost Estimations with Risk and Opportunity Management

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Abstract

Oil and gas exploration is a high-risk, high-reward industry where companies must balance the potential for significant profits with the possibility of substantial losses. To help mitigate this risk, companies use risk and opportunity management techniques to assess the likelihood and impact of various outcomes. One critical aspect of risk and opportunity management in the oil and gas industry is accurately estimating drilling costs to increase the probability of success (POS). Traditional methods of drilling cost estimation have relied on deterministic models that assume fixed values for various inputs, such as drilling time and depth. However, these models could be more robust in accounting for the numerous variables that can impact drilling costs. In addition, most of these models are developed early in the Well Delivery Process (WDP); thus, comprehensive risk mitigations related to operations performance are rarely considered as part of the analysis.

Probabilistic drilling cost estimation is a more advanced approach that uses statistical analysis and simulation techniques to estimate drilling costs. This method considers the inherent uncertainty and variability of drilling operations, allowing for more accurate risk and opportunity assessments by using probability distributions to forecast a range of estimated costs to drill the well. Using probabilistic drilling cost estimation, companies can gain a more comprehensive understanding of the range of potential drilling costs for a given investment level and the certainty of different outcomes. This information

can be used to develop more effective risk and opportunity management strategies, including contingency planning, risk mitigation, and resource allocation to commonly seen problems that occur during drilling. These models can also help companies identify and capitalize on opportunities that may have not been apparent with traditional deterministic models. For example, by identifying areas with higher-than-expected drilling efficiency, companies can adjust their drilling strategies to take advantage of these opportunities, potentially resulting in significant cost savings and increased profitability.

This paper presents the detailed mechanics of applying the POS cost methodology to illustrate how the process works on a sample case. The sample risk and opportunity factors derived in a previous publication for different stages of the well drilling life cycle will be input into the commercially available Crystal Ball Monte Carlo Software tool to determine the estimated POS of achieving the project cost (Expected Monetary Value). Note that although POS can be performed for multiple stages and factors (i.e., cost, schedule, and performance) for the effects of this work, only POS cost will be addressed. The methodology provided can be adapted for multiple applications in future work. The goal is to provide a tool that will enable more accurate and comprehensive estimates of drilling costs. This method can help companies make more informed decisions, reduce risk, and increase profitability. The post-mortem analysis from a sample well shows that if the proposed methodology had been implemented, the following could have been improved:

1. Certainty to remain within the baseline budget from 41.37% to 99.11%. This provides approval for expenditure (AFE) assurance and increases the likelihood of reaching well objectives.

2. The drilling cost saving of $338,207 (2% of baseline cost) may look insignificant. Still, it represents added gains on top of already reaching the well objectives, which could have been more questionable before implementing the mitigation strategies.

Note that this accounts for the cost incurred by the mitigations and the time efficiency improvements.

3. Most investors require at least an 80% certainty depending on each project's risk and uncertainty level. Based on the analysis results, to achieve an 80% certainty for the Tornado sample well an estimated budget between $15,932,883 and $16,703,504 would be required. This would represent a minimum additional investment of slightly over $1,000,000 compared to the baseline case (no mitigations).

1. Introduction

In the oil and gas industry, drilling a well is a crucial process that requires significant time and money. The cost of drilling a well varies depending on various factors such as the location, depth, type of rock formation, and drilling technology used. The success of drilling a well also depends on several factors, such as geology, reservoir properties, and drilling efficiency. Therefore, estimating the Probability of Success (POS) is critical in deciding whether to invest in a drilling program. POS is generally associated with geological POS, meaning the chances of making a discovery. However, for this work, POS is defined as the likelihood of achieving the well objectives within one or more of the three main variables: Performance, Schedule, and Cost. The POS estimate helps the company to decide whether to invest in drilling the well, how much to spend on drilling and completion, and what risk mitigation measures to implement.

The potential value of POS to the oil and gas industry is significant. POS provides a critical tool for evaluating the viability of a project, estimating the potential returns on investment, and managing risk and opportunities. Using POS, companies can make informed decisions about where to allocate their resources and prioritize their exploration and development activities. For example, an operator with an extensive portfolio of exploration projects may use POS to identify those with the highest likelihood of success and allocate their resources accordingly. This can help to optimize their investment strategy and increase the overall profitability of their exploration activities.

POS can also be used to manage risk in the oil and gas industry. Exploration and development activities are inherently risky, with significant uncertainty in predicting a project's potential success. By using POS to evaluate the risk associated with different tasks, companies can make informed decisions about managing that risk, for example, by hedging against potential losses or diversifying their portfolio to reduce their overall exposure to risk. Altogether, the potential value of the POS to the oil and gas industry lies in its ability to provide a systematic and objective approach to evaluating the likelihood of success in exploration, appraisal, and development activities. Using POS, companies can optimize their investment strategy, manage risk, and ultimately increase profitability. Thus, the best value alternatives are assembled into the final well strategy, allowing decision-makers during planning and drilling operations with a method that incorporates opportunities, consequences, and probabilities associated with them. Such a method can become a critical competitive advantage and a discriminator against strategies with a less favorable projected value. This could reduce uncertainty and enable real-time strategic decisions with the available and most viable options.

The following sections of this work present an overview of the currently available tools for Probability of Success (POS) estimations. The authors show the procedural steps for creating and managing cost estimations as part of the well delivery process and the requirements for proper implementation of POS for this purpose. In addition, the model developed for the POS Cost determination of a sample well is presented. The model objectives, methodology, assumptions, and results are discussed. The work concludes by addressing the results and findings of the case study well and future work.

2. Currently available tools for POS estimations

Various tools and methods are available to estimate the Probability of Success (POS) in the oil and gas industry. These tools range from simple heuristics to complex numerical models, and they all rely on different data sources and assumptions. However, the choice of method depends on the availability of data, level of uncertainty, and project complexity. While some methods are relatively simple and require less data, others are more complex but provide a more comprehensive risk and uncertainty assessment. The accuracy of POS estimates depends on the quality and quantity of data available, the experience of the team analyzing the data, and the complexity of the geological and engineering challenges posed by the prospect.

Some of the currently available tools for POS estimations are as follow:

- **Decision Analysis**: This method uses decision tree analysis to estimate the POS. The method involves breaking the project into discrete decisions and assigning probabilities to each decision node. The POS is then calculated as the probability of success for the entire decision tree.
- **Data-Driven Methods**: With the recent advances in data analytics, several data-driven methods have emerged for estimating POS. These methods use machine learning algorithms to analyze large amounts of data from past projects and identify patterns and relationships that can be used to estimate the POS for a new project. These methods are still in the early stages of development but could revolutionize how POS is assessed.
- **Monte Carlo Simulation**: This method involves running multiple simulations of the project to estimate the POS. The method consists of defining the range of uncertainty associated with each variable in the project and then using random

sampling techniques to generate many scenarios. The POS is then calculated as the percentage of simulations that result in a successful project. This method is the most complex of the methods discussed so far, but it provides a more comprehensive assessment of uncertainty and allows for incorporating multiple variables. Some proprietary packages like Crystal Ball (from Oracle) and @Risk (from Palisade) are available to run these analyses.

This work centers on the applications of Montecarlo Simulations to determine the probability of success for the Well Delivery Process using the Crystal Ball package from Oracle.

3. Cost Estimations to Create and Manage a Well-Delivery Process

Creating and managing a well delivery process includes the expenses associated with planning, drilling, completing, and producing a well. The cost of drilling a well depends on various factors such as the location, depth, type of rock formation, and drilling technology. Drilling a well can range from a few hundred thousand dollars to several million dollars.

The well delivery process involves various stages, including:

- Planning and site preparation
- Drilling the wellbore
- Evaluating and completing the wellbore
- Producing hydrocarbons

Each of these stages incurs different costs, which depend on the geological and engineering challenges posed by the prospect, the drilling technology used, and the level of complexity involved.

Implementing POS for the cost to create and manage a well delivery process involves estimating the probability of success for the drilling program and determining the appropriate level of investment required to achieve success.

Step 1 Estimating the Probability of Success: The POS estimate should consider various factors, such as the geological and engineering challenges posed by the prospect, the quality and quantity of data available, and the level of uncertainty involved in the estimate. The POS estimate should also consider the risk mitigation measures that can be implemented to improve the chances of success.

Step 2 Determining the Appropriate Level of Investment: The second step in implementing POS for the cost to create and manage a well drilling program is determining the appropriate investment level required to achieve success. This involves considering the estimated cost of drilling the well and the estimated POS. The necessary level of investment should consider the expected return on investment (ROI) for the drilling program, the level of risk involved, and the company's financial resources. If the estimated POS is low, the company may decide to invest less in the drilling program or postpone the program until the estimated POS improves. Conversely, if the estimated POS is high, the company may invest more in the drilling program to increase the chances of success and maximize the expected ROI. The appropriate level of investment should also consider the potential impact of cost overruns and delays on the drilling program. The drilling program should be designed to minimize the risks of cost overruns and delays by incorporating best practices in project management, risk management, and supply chain management.

Step 3 Monitoring and Adjusting the Plan: The third step in implementing POS for the cost to create and manage a well drilling program is to monitor the program’s progress and adjust the plan as necessary. This involves regularly reviewing the drilling program's performance, comparing it to the initial plan, and identifying any deviations from the plan. If the drilling program is not meeting the expected performance, the company should consider adjusting to improve the chances of success. This may involve increasing or decreasing the level of investment, changing the drilling technology used, or implementing risk mitigation measures to reduce uncertainty.

4. Implementation of POS Cost to Manage a Well Delivery Process

The following section describes the probabilistic approach to develop the POS cost model that can be used through the project life cycle of the well delivery process. This section will discuss the objective and scope of the model and methodology used and the required inputs and outputs.

Objective and Scope

The main objective is to generate a well-cost spreadsheet that will enable forecasting and risk analysis to predict the cost range and days necessary to drill a well. For this, the commercially available Crystal Ball from Oracle will be used. Incorporating $POS_{Well\ Delivery}$ enables a non-biased, statistically based approach for new venture-opportunity evaluations, AFE preparation, and management, informed decision-making at critical points in the project, and identification of contingency strategies. The intent of this application is for it to be used at different stages of the project. This approach enables the incorporation of uncertainties and associated risks as part of the well delivery process. Thus, the model considers the risks, opportunities, and potential contingencies or scope changes. This is a big benefit of approaching well construction estimation probabilistically.

The project cost estimates are based on multiple assumptions with high uncertainty. For this work, the baseline budgets are based on two main components: (a) total days on the well (measured on days), and (b) detailed casing program (measured on footage/depth). Thus, the well is broken down into multiple well-specific sequences of operations. The level of detail of the project cost estimation will depend on the level of detail offset data available, risks/opportunity identifications, or engineering judgment. For this sample well , which the authors will refer to as the Tornado well, the project cost estimates on the AFE have been divided into three main categories: fixed cost, depth costs, and time costs (see Table 3-1). These should be evaluated on a well-by-well basis, depending on the level of existing data. For example, the days per footage, days per completion, and overall spread rate with an allowance for tangibles and high-risk levels may be the only components of the scoping estimate.

Table 3-1: Typically Accounted Cost Categories

Cost Category	Description
Time-Dependent	• Time on location (days)
	• Time required to drill the well (days)
	• Rig costs. Rig rates can vary widely (day rate)
	• Time-related services: fluids, boats, mud logging, MWD/LWD (days).
Depth Dependent	• Tangible equipment based on weight, grade, and length of the casing, wellhead equipment, and unit costs.
	• Depths are varied according to uncertainty
Fixed Cost	• Range and distribution are affected by the remoteness and conditions and are generally not tied to the time for drilling
	• Location preparation costs
	• Mobilization/demobilization costs for drilling units and personnel
	• Rig stand-by rates, fuel use
	• Turn-key services

Methodology and Case Study

A comprehensive process is in place to perform the $POS_{well\ delivery}$ approach. The following present a high-level representation of the approach:

a) The process starts with defining a baseline cost estimate for the well. Since this application is on the sample well, a round table with subject matter experts (SMEs) defined the baseline cost estimate and its mitigation cost and associated strategies, see Figure 3-1. Note that a contingency budget is typically defined as a percentage of the AFE (Approval for Expenditure). For the sample Tornado well, 10% was used.

The baseline cost estimate is divided into two main categories: (1) No Mitigation AFE, and (2) Mitigation AFE. Each case presents Best Case, Most Likely Case, and Worst Case. These are all derived from SMEs' Total Days of Drilling time estimation (see appendix A). Table 3-2 summarizes the two categories and the possible three scenarios corresponding to each.

Table 3-2 Summary of Cost Breakdown for Sample Well Based on Mitigations vs. No Mitigation Time Estimates

	Case	Total Days	Total Cost
1. No Mitigations	No Mitigation Best Case (1.1)	127	$13,843,259
	No Mitigation Most Likely Case (1.2)	152	$15,587,624
	No Mitigation Worst Case (1.3)	185	$17,668,478
2. Mitigations	Mitigation Best Case (2.1)	105	$13,848,347
	Mitigation Most Likely Case (2.2)	131	$15,249,417
	Mitigation Worst Case (2.3)	152	$16,426,648

As a baseline budget for this work, the No Mitigation Most Likely Case ($15,587,624 - labeled 1.2, from the table below) has been selected for the initial $POS_{well\ delivery}$ estimation. The additional budgets are used to develop the probability distributions, which are explained in detail in subsequent sections of this work. Then, the same analysis is performed on the Mitigation Most Likely Case (e.g., 2.2 - $15,249,417), and the results are assessed to determine the value of risks/mitigation incorporation to ensure meeting the well objectives.

CODE	DESCRIPTION	No mitigation			Mitigation		
		COST (U.S DOLLARS)			COST (U.S DOLLARS)		
		Best Case	Most Likely	Worst Case	Best Case	Most Likely	Worst Case
0101	Daywork Drilling	$2,548,000	$2,948,000	$3,468,000	$2,100,000	$2,620,000	$3,048,000
0201	Location/Road Prep.; Site Survey	$130,000	$130,000	$130,000	$130,000	$130,000	$130,000
0202	Location Cleanup	$40,000	$40,000	$40,000	$40,000	$40,000	$40,000
0203	Permitting Services & Fees	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000
0501	Open Hole Logs	$65,000	$65,000	$65,000	$65,000	$65,000	$65,000
0502	DST & Well Testing Services	$250,000	$250,000	$250,000	$250,000	$250,000	$250,000
0503	Mud Loggers	$145,860	$178,860	$221,760	$118,800	$151,800	$178,860
0504	Formation Evaluation Services (LWD)	$261,000	$310,500	$382,500	$202,500	$261,000	$310,500
0601	Diesel Fuel	$152,880	$176,880	$208,080	$126,000	$157,200	$182,880
0700	Water (non-mud)	$6,370	$7,370	$8,670	$5,250	$6,550	$7,620
0801	Drlg./Compl. Fluids	$518,700	$628,700	$771,700	$428,500	$538,500	$628,700
0802	Water and Brine - Drilling	$85,920	$101,920	$122,720	$72,800	$88,800	$101,920
0803	Liquid Mud Purchased	$130,000	$130,000	$130,000	$130,000	$130,000	$130,000
0804	Completion Fluids: Muds or Brines	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000
0805	Solids Control / Mud Equipment	$110,500	$135,500	$168,000	$90,000	$115,000	$135,500
0806	Mud Transportation	$40,000	$40,000	$40,000	$40,000	$40,000	$40,000
0901	Cementing Materials and Service	$190,000	$190,000	$190,000	$190,000	$190,000	$190,000
0902	Cementing Accessories - Floats, etc.	$125,000	$125,000	$125,000	$125,000	$125,000	$125,000
1201	Land transportation	$202,320	$238,320	$285,120	$172,800	$208,800	$238,320
1401	Cased Hole Logging and Perforating	$50,000	$50,000	$50,000	$50,000	$50,000	$50,000
1402	Stimulation - Fracturing	$2,520,000	$2,880,000	$3,240,000	$2,880,000	$2,880,000	$2,880,000
1501	Bits Purchased	$200,000	$200,000	$200,000	$200,000	$200,000	$200,000
1502	Stabs., H.O., U.R.,- Non Direct. Related	$45,600	$59,100	$74,100	$40,500	$51,000	$59,100
1601	Drill String Rentals	$106,080	$130,080	$161,280	$86,400	$110,400	$130,080
1602	Well Control Rentals (Non-MPD)	$56,700	$66,700	$79,700	$45,500	$58,500	$69,200
1603	Rig Monitoring Equip.	$85,050	$100,050	$119,550	$68,250	$87,750	$103,800
1604	Dir. Drilling, Rental/Service	$359,600	$427,800	$527,000	$279,000	$359,600	$427,800
1605	Dir. Drilling Surveying/MWD	$220,400	$262,200	$323,000	$171,000	$220,400	$262,200
1606	Snubbing Services	$136,500	$136,500	$136,500	$97,500	$136,500	$169,000
1800	UBD/MPD Equipment & Services				$390,000	$494,000	$598,000
2001	Casing Running, Hammer, Torque Turn	$225,000	$225,000	$225,000	$225,000	$225,000	$225,000
2002	Waste Disposal	$63,700	$73,700	$86,700	$52,500	$65,500	$76,200
2003	Dist. Ser. Chg. - Non Labor	$50,960	$58,960	$69,360	$42,000	$52,400	$60,960
2004	Well Control Insurance	$31,850	$36,850	$43,350	$26,250	$32,750	$38,100
2005	Communications/Computer Rental	$25,480	$29,480	$34,680	$21,000	$26,200	$30,480
2006	Drilling Labor/Supervison	$331,240	$383,240	$450,840	$273,000	$340,600	$396,240
2101	Mobilization\Demobilization	$112,000	$112,000	$112,000	$112,000	$112,000	$112,000
3001	Casing & Tubing	$2,518,071	$2,797,857	$3,077,642	$2,797,857	$2,797,857	$2,797,857
3101	Wellhead Equipment	$165,000	$165,000	$165,000	$165,000	$165,000	$165,000
3102	Downhole Equipment	$240,000	$240,000	$240,000	$240,000	$240,000	$240,000
0000	Contingency (Management Reserve)	$1,258,478.10	$1,417,056.70	$1,606,225	$1,258,940.67	$1,386,310.67	$1,493,331.67
		$13,843,259	**$15,587,624**	**$17,668,478**	**$13,848,347**	**$15,249,417**	**$16,426,648**

Figure 3-1: Sample Tornado Well Cost Estimations

b) Once the baseline budget is defined, the major contributions to the cost are evaluated. As expected, those costs were correlated with the top risks and opportunities identified by the SMEs in a previous assessment for this specific application. For this, a Tornado Chart (Figure 3-2) was developed.

The Tornado diagram (Figure 3-2) shows the uncertainties associated with the drilling cost estimates. This tool prioritizes the uncertainties and risks based on their hierarchical influence on the well cost. The Tornado Diagram uses the Spearman rank-order correlation coefficient, calculated on the ranks of the parameters' values rather than on the raw values themselves. The Tornado Diagram enables the prioritization of the highest impact costs or events for mitigation or management over the lowest impact cost or events.

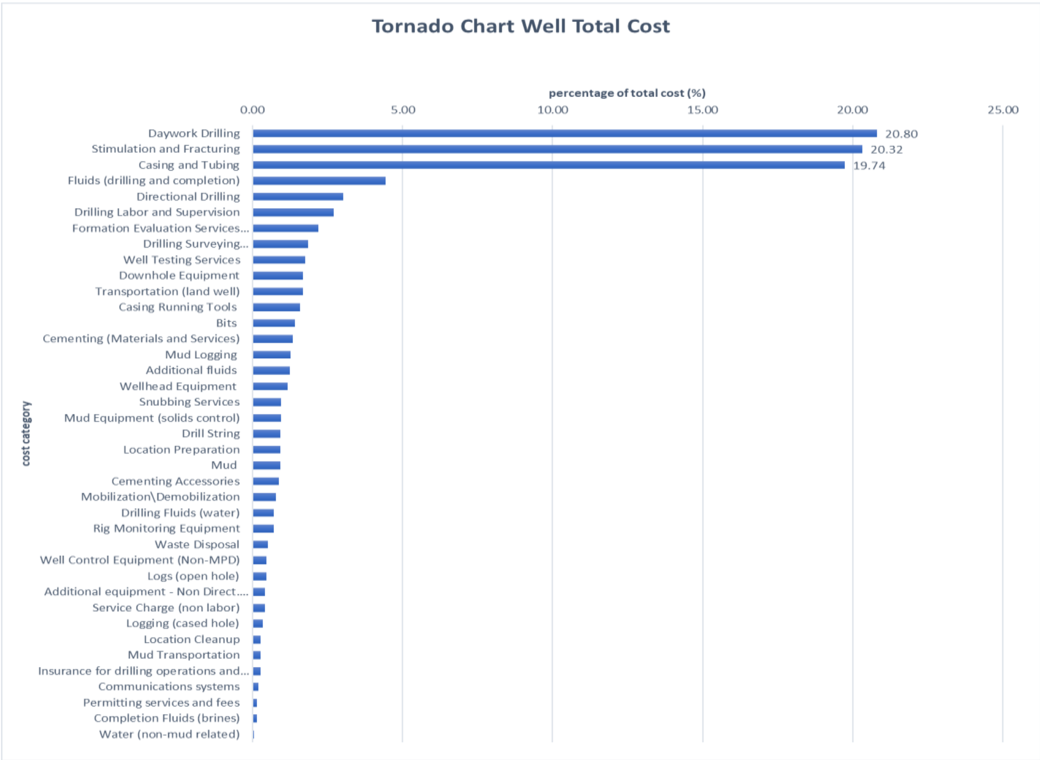

Figure 3-2: Tornado Chart Well Cost Contributions for Sample Well

Based on the Tornado analysis, and as presented in Table 3-3, it can be observed that the top five main contributors to the well cost estimations account for 68.33% of the budget, and significant risks are associated with each one. Later in the analysis, these will become the main assumptions for the approach developed.

Table 3-3 Summary of Well Cost and Associated Risk Items Sorted in Descending Order

Code	Description	Risk Associated	% of Total	Percent Rank	Total % Contribution
0101	Daywork Drilling	Execution errors, NPT, Pressure and temperature, Type of Well	20.80	1	68.33%
1402	Stimulation and Fracturing	Improper project feasibility	20.32	2	
3001	Casing and Tubing	Frequent design changes Delay in decision making	19.74	3	
0801	Fluids (drilling and completion)	Frequent design changes Delay in decision making	4.44	4	
1604	Directional Drilling	Rig characteristics	3.02	5	
2006	Drilling Labor and Supervision	Delay in decision making	2.70	6	
0504	Formation Evaluation Services (Logging While Drilling)	Unreliable data	2.19	7	
1605	Drilling Surveying (Measuring While Drilling)		1.85	8	
0502	Well Testing Services		1.76	9	
3102	Downhole Equipment		1.69	10	
1201	Transportation (land well)		1.68	11	
2001	Casing Running Tools		1.59	12	
1501	Bits		1.41	13	
0901	Cementing (Materials and Services)		1.34	14	
0503	Mud Logging		1.26	15	
0601	Additional fluids		1.25	16	
3101	Wellhead Equipment		1.16	17	
1606	Snubbing Services		0.96	18	
0805	Mud Equipment (solids control)		0.96	19	
1601	Drill String		0.92	20	
0201	Location Preparation		0.92	21	
0803	Mud		0.92	22	
0902	Cementing Accessories		0.88	23	
2101	Mobilization\Demobilization		0.79	24	
0802	Drilling Fluids (water)		0.72	25	
1603	Rig Monitoring Equipment		0.71	26	
2002	Waste Disposal		0.52	27	
1602	Well Control Equipment (Non-MPD)		0.47	28	
0501	Logs (open hole)		0.46	29	
1502	Additional equipment - Non Direct. Related		0.42	30	
2003	Service Charge (non labor)		0.42	31	
1401	Logging (cased hole)		0.35	32	
0202	Location Cleanup		0.28	33	
0806	Mud Transportation		0.28	34	
2004	Insurance for drilling operations and well control		0.26	35	
2005	Communications systems		0.21	36	
0203	Permitting services and fees		0.14	37	
0804	Completion Fluids (brines)		0.14	38	
0700	Water (non-mud related)		0.05	39	

c) Subsequently, a Crystal Ball model was developed and executed. The result is a spreadsheet with line-item cost estimates entered as single values or distributions. For this sample Tornado well all the inputs are assumed to be independent. Any dependency relationship has been incorporated as part of the calculations of those items. This will be explained in the subsequent sections (Section 5. Crystal Ball Model and Metrics to Define Success, and Section 6. Study Results and Findings).

The Crystal Ball simulation tool from Oracle allows to model and analyze complex systems and events using Monte Carlo simulation techniques. The Monte Carlo simulation is a statistical method that uses random sampling to simulate the probability of different outcomes or events. This gives users a comprehensive understanding of the risks and uncertainties involved in their operations. The Crystal Ball simulation generates multiple scenarios or outcomes (forecast) based on input variables or assumptions. Interpreting the Crystal Ball results requires careful analysis of the simulation output data. The software generates a wide range of statistical measures, including mean, standard deviation, and percentile values, which can be used to analyze the simulation outcomes and identify areas of risk and uncertainty.

Results of $POS_{well\ delivery}$ analysis were assessed by comparing with historical results, and if there were any significant deviations, the initial input assumptions were re-evaluated.

5. Crystal Ball Model and Metrics to Define Success

The Crystal Ball software from Oracle is a powerful tool for analyzing risk and uncertainty in various applications. To use the software effectively, input data that accurately reflects the analyzed system or scenario must be provided. The inputs required for the Crystal Ball software from Oracle include deterministic and stochastic inputs, presented as Assumptions. Other inputs include simulation settings, simulation outputs in Forecast variables, and sensitivity analysis. Accurate and appropriate input data is critical to obtaining meaningful results from the software. For the sample well case, the author has selected appropriate probability distributions and performed sensitivity analyses as needed to ensure the accuracy and reliability of the results based on available data.

The accuracy of the simulation is dictated by two factors (a) the number of trials, or length, of the simulation, and (b) the sampling method. For this sample well, a total of 10,000 trials have been used. Similarly, the sampling method used was Monte Carlo. The Monte Carlo sampling generates “what-if” type scenarios based on random sampling based on pre-defined probabilistic distributions.

Inputs Assumptions and Forecast Variables

The assumptions and forecast variables used in the Crystal Ball Oracle software are critical inputs to generate scenarios and outcomes in the Monte Carlo simulation. Assumptions are variables that are known with a high degree of certainty and are used to set the initial conditions for the simulation. These assumption variables provide a baseline against which the outcomes can be measured. The assumptions selected for the sample well correspond to the top five risks/opportunities identified in Table 3-3.

On the other hand, forecast variables are subject to random fluctuations. A forecast is a formula or output cell the user wants to simulate and analyze (Oracle, 2012). The forecast variables are typically modeled using probability distributions, representing the likelihood of different values occurring. The Total Well Cost has been designed as the forecast cell for the sample well. This is further discussed in the results section.

The accuracy of the assumptions and forecast variables used in the Crystal Ball software is critical to the accuracy of the simulation results. Thus, we must carefully select appropriate probability distributions for the forecast variables and validate the assumptions used in the simulation to ensure that they are accurate and reliable. Sensitivity analysis may also identify the key drivers of risk and uncertainty in the system or scenario being analyzed.

Selecting Distributions

Significant time was invested in ensuring that the input distributions accurately represented the average and deviation of the analyzed offset data for the sample well. Choosing the appropriate distribution type for a specific parameter depended on various factors, such as offset/historical data, essential principles, subject matter expert (SME) judgment, and understanding of the given parameter.

Typically used distribution profiles include: 1) normal, 2) uniform, and 3) triangular distributions (de Wardt & Peterson, 2015). In the case of this well, the distribution type has been chosen to have the appropriate level of variability and the correct symmetry (skewness). As presented in Table 3-4, there are three categories of Cost: Time-dependent, depth-dependent, and fixed cost. Each category has been evaluated based on the subject matter experts and literature survey, and the triangular distribution has been selected for this application.

Table 3-4 Probabilistic Distributions typically used per Cost Category.

Cost Category	Description	Distributions
Time-Dependent	Time on location (days)	No. of Days = normal, log normal, or triangular. Daily Rate = Uniform distribution, triangular, or normal
	Time required to drill the well (days)	
	Rig costs. Rig rates can vary widely. (day rate)	
	Time-related services: fluids, boats, warehouses, mud logging, MWD/LWD (days).	
Depth Dependent	Tangible equipment based on weight, grade, and length of the casing, wellhead equipment and unit costs.	Uniform or triangular distribution is also applied to unit prices ($/ft)
	Depths are varied according to uncertainty	
Fixed Cost	Range and distribution are affected by the remoteness and conditions and are generally not tied to the time for drilling	
	Location preparation costs	
	Mobilization/demobilization costs for drilling units and personnel	
	Rig stand-by rates, fuel use	
	Turn-key services	

Simulation Outputs

The output of the probabilistic analysis and its interpretation is critical to communicate the effect of uncertainties to decision-makers. Interpreting the Crystal Ball software results from Oracle required careful analysis of the simulation output data. The software generates a wide range of statistical measures, including mean, standard deviation, and percentile values, which were used to analyze the simulation outcomes and identify risk and uncertainty areas.

For the sample well a series of sensitivity analyses were performed to identify the key drivers of risk and uncertainty in the analyzed scenario. By varying the input assumptions and forecast variables, the authors analyzed how changes in these variables affect the output and identified areas of the system most sensitive to changes in these variables.

The main goal for the $POS_{well\ delivery}$ is to provide for Total Well Cost distribution estimation based on a probabilistic assessment of risk and uncertainty. To have a comprehensive understanding of the results, the following aspects will be evaluated: (a) Forecast Charts, (b) Certainty ($POS_{well\ delivery}$), (c) Descriptive Statistics, (d) Percentiles.

Forecast Charts

Forecast charts represent the frequency distributions of a value occurring in a given interval in a graphical way (Oracle, 2012). The forecast chart in Crystal Ball typically includes the following components:

- Forecasted values: These are the predicted values for the time series based on the chosen forecasting model.
- Confidence interval: This is the range of possible values within which the actual future values will likely fall with a certain degree

of confidence. It is typically represented as a shaded area around the forecasted values.

- Prediction interval: This is a wider range of possible values, including the expected values and the impact of random variation or uncertainty. It is represented as a wider shaded area around the forecasted values.

Certainty

Certainty is the percentage chance that the forecast value will fall within a specified range. This is obtained from the forecast chart, which shows the range of results for each forecast variable and the probability, or certainty, of achieving results within a range. By default, the certainty range is from negative infinity to positive infinity. The certainty for this range is always 100 percent. However, estimate the chance of a forecast result falling in a specific range from zero to infinity. For the sample well, the Certainty was compared against the Baseline Budget of $15,587,624 (No Mitigation Most Likely Case, see Table 3-2). Thus, the goal was to determine the chances of drilling the well and remaining within the initial budget estimations. Additionally, the impact of each risk item was used to evaluate their individual and conjunct impact on the Certainty.

Descriptive Statistics

Mode – In statistics, mode measures central tendency representing a dataset's most frequently occurring value. The value appears the greatest number of times in the dataset. Thus, this value occurs most often during the ten thousand Monte Carlo simulation runs. On the probability frequency chart, it is the value at the highest point in the curve.

Mean – Represents the arithmetic average of all the outcomes. It is calculated by adding all the values in the dataset and dividing them by the total number of values. This metric is the actual outcome value instead of the frequency of occurrence. The mean values are commonly used for AFE or when aggregating a single well result (Akins, Abell, & Diggins, 2005).

Standard deviation - Measures a dataset's variation or dispersion relative to its mean. It measures how much the individual data points deviate from the mean.

Percentiles

Percentiles are a statistical measure that divides a dataset into 100 equal parts. They describe the relative position of a particular value within a distribution of values. There are 99 percentiles, starting from P1 to P99. The most used percentages when interpreting the results are P10, P50, and P90 percentiles. A benefit of the P90 cost estimate is that it can be used to determine the contingency budget for a given well (de Wardt & Peterson, 2015).

For this work, the following key percentiles for the outputs from the probabilistic estimations will be included:

- P10: represents the 10th percentile, which is the value of the duration cost corresponding to 0.1 on the cumulative probability axis. There is a 10% probability that the cost will be less than this.
- P50: represents the median, a measure of the central tendency of the estimations.
- P90: represents the 90th percentile, which is the value of the duration cost corresponding to 0.9 on the cumulative probability axis. There is a 10% probability that the cost will be more than this.

6. Study Results and Findings

The following analysis evaluates $POS_{well\ delivery}$ for a sample land well in Texas. Two different budget estimations will be analyzed and compared to determine the impact of risk mitigation budgets and strategies on the probability of success.

There are two cases presented in this work:

- Case 1: Baseline Budget (No Mitigations, All Risks Included)
- Case 2: Mitigated Budget (All Mitigations, All Risks Included)

Each case will be evaluated on separate analyses, and the results will be compared based on certainty, descriptive statistics, and project historical information. Since the cases are evaluated separately, assumptions and forecast variables will be defined individually. Furthermore, the top five risk items and their impact on the total well cost have been analyzed.

Table 3-5 presents the summary of all the cases explored. The following sections present details of all the cases, assumptions, and outputs from the Monte Carlo simulations.

The following findings can be summarized:

When comparing Case 1 versus Case 2, there is a significant improvement in the certainty level ($POS_{well\ delivery}$) from 41.37 to 99.11 for each case, respectively, representing an increase of 57.74.

The cost of transitioning from Case 1 (no mitigations, $ 15,587,624) to Case 2 (mitigations, $ 15,249,417) is considered negligible for this case. The difference in time efficiency and mitigation of potentially catastrophic risks payoff off the cost of the mitigation associated with Case 2. Once the historical data was analyzed. It was determined that some of the risk's items' values became uniform due to reducing the associated risks. Similarly, comparing on person-days required to drill the well, the most likely Case 1 (no mitigations) becomes the worst case in Case 2 (mitigations). This provides additional assurance to meet AFE requirements.

Table 3-5 Monte Carlo Simulations Results for Sample Tornado Well

Case	Certainty Level	Mean	Median	Standard Deviation	Variance	Coeff. of Variation	Minimum	Maximum	Range Width	Std Error of Mean
Case 1: Total Well Cost No Mitigation, All Critical	41.37	$15,656,789	$15,650,006	$299,283	$89,570,229,715	0.0191	$14,687,698	$16,654,655	$1,966,957	$2,993
Case 2: Total Well Cost Mitigation, All Critical	99.11	$15,204,487	$15,211,081	$227,880	$51,929,071,662	0.0150	$14,526,912	$15,844,006	$1,317,094	$2,279
Total Well Cost No Mitigation, Risk Item#1	44.23	$15,628,772	$15,618,449	$207,197	$42,930,656,881	0.0133	$15,154,880	$16,150,233	$995,353	$2,072
Total Well Cost No Mitigation, Risk Item#2	42.92	$15,600,567	$15,597,876	$56,748	$3,220,289,388	0.0036	$15,468,822	$15,744,364	$275,542	$567
Total Well Cost No Mitigation, Risk Item#3	50.35	$15,589,889	$15,589,603	$161,615	$26,119,516,512	0.0104	$15,195,487	$15,978,305	$782,818	$1,616
Total Well Cost No Mitigation, Risk Item#4	40.51	$15,599,114	$15,596,755	$37,437	$1,401,524,750	0.0024	$15,514,598	$15,695,076	$180,478	$374
Total Well Cost No Mitigation, Risk Item#5	49.55	$15,589,059	$15,588,912	$125,396	$15,724,034,502	0.0080	$15,282,741	$15,891,242	$608,500	$1,254

The Total Well Cost range also differs significantly from $1,966,957 for Case 1 to $1,317,094 for Case 2. This represents a difference of over half a million dollars ($649,863). Although the minimum well cost is expected to be relatively the same, the maximum expected cost could be approximately $810,649 higher for Case 1.

Although a comprehensive statistical analysis has not been conducted, some of the statistical measurements (i.e., Mean, Median, and Variance) from Crystal Ball output will be briefly discussed:

- Case 1 has a Mean of $15,656,789 which is slightly higher than Case 2 ($15,204,487). This allows us to infer that the total well costs for the Case 1 estimation are higher than for Case 2, making this a project with a slightly higher investment than Case 2. This by itself may not represent a deal breaker, but there is no guarantee that the risk or mitigations can be managed.

- Similarly, Case 1 has a higher Median than Case 2, $15,650,006 versus $15,211,081, respectively. Although it may not be statistically significant, depending on sample size and variability of the sample, it does imply that Case 1 has a higher median than Case 2, this suggests that the distribution of cost estimates in Case 1 may be skewed towards higher values compared to Case 2.
- For this application, Case 1 has a significantly higher variance than Case 2. This suggests that the cost estimates in Case 1 may be more spread out or have more variability compared to Case 2.
- The implications of these values for comparing two cases are differences in the mean, median, variance, and standard error of the mean between the two cases. These differences may suggest that the cost estimates in Case 1 are generally higher, more spread out, and more variable compared to Case 2. However, further analysis is required to fully understand the data's distribution and characteristics and determine whether these values' differences are statistically significant.

This approach has multiple applications depending on the end consumer's needs. Although it was not the case for this application, in cases where the budget is limited, multiple permutations of the associated risks can be evaluated, and its impact on POS will enable to prioritize individually those with greater impact on the total cost of the well. For this specific work, even though they were evaluated separately (see Appendix B), the mitigated total well cost already represented an improvement from the initial baseline. However, this option remains available as part of the additional applications of the tool.

Definition of Assumptions

The following distributions have been pre-defined by the subject matter experts (SME) panel based on (1) days to drill the well for each case and (2) experience and historical data from similar projects. Note that some assumptions become uniform values by incorporating mitigation strategies in the budget estimations. Furthermore, the budget and distribution associated with these strategies have been incorporated into Case 2.

Five assumptions are considered in the model, which corresponds to the account activities associated with the top five risk items identified by the SME panel (see Figure 3-3).

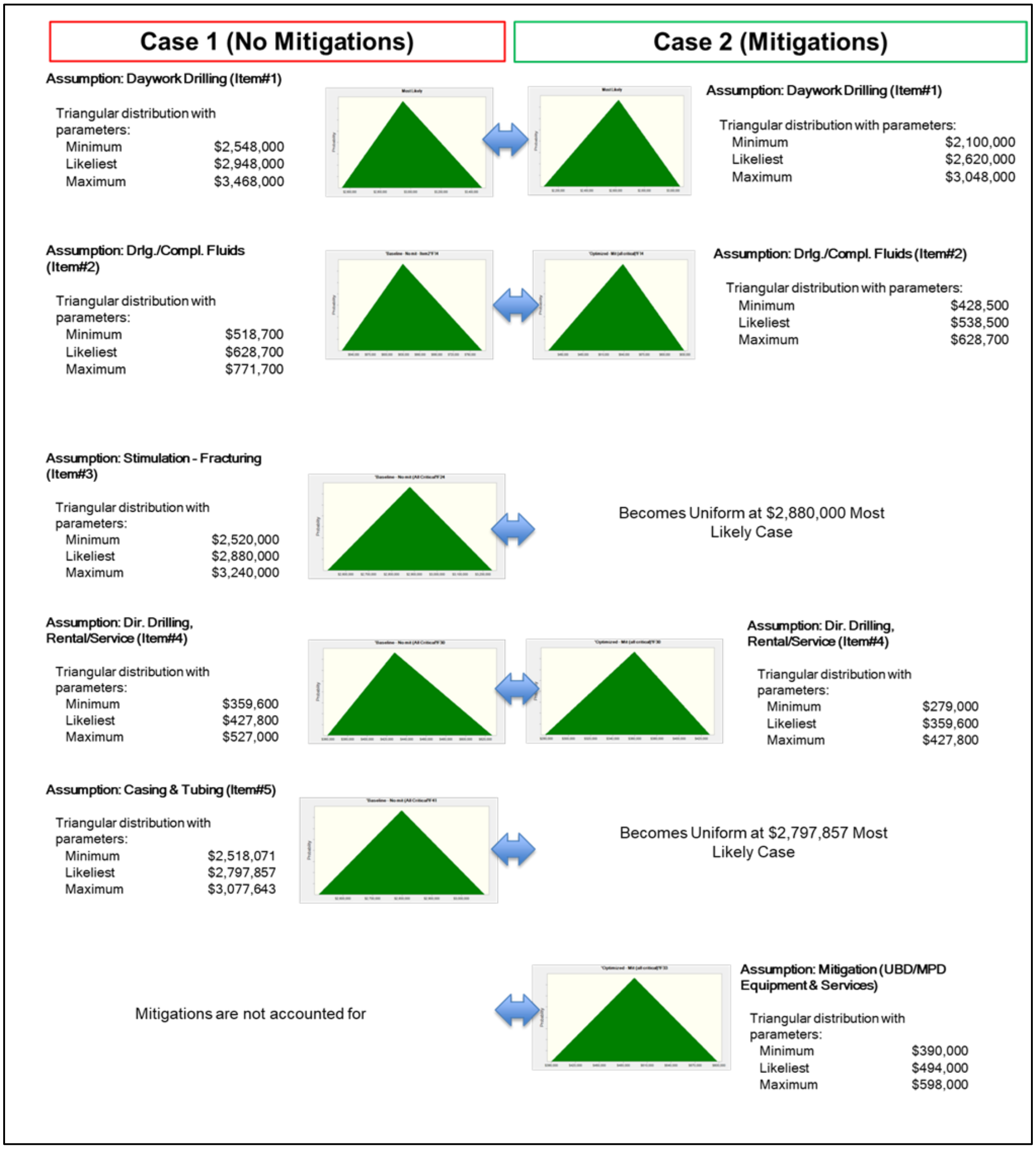

Figure 3-3: Assumptions Variable Definitions - Based on SMEs Experience

Case 1: Baseline Budget (No Mitigations, All Risks Included)

Case 1 is considered the baseline budget case. This case represents the sample Tornado well initial budget, not accounting for mitigation strategies. The top five risks were incorporated into the Crystal Ball analysis for this case. As can be seen from Figure 3-4, the $POS_{\text{well delivery}}$ is estimated at 41.37%, with a baseline budget of $15,587,624. For Case 1, the P10, P50, and P90 values correspond to $16,048,459, $15,649,922, and $15,273,506, respectively, which implies that the likelihood of the total well cost being below the baseline budget is less than 50%. Most investors require at least 80% certainty depending on each project's risk and uncertainty level. Thus, this project would be considered a no-go if only considering the POS (not including other economic indicators, such as ROI, etc.).

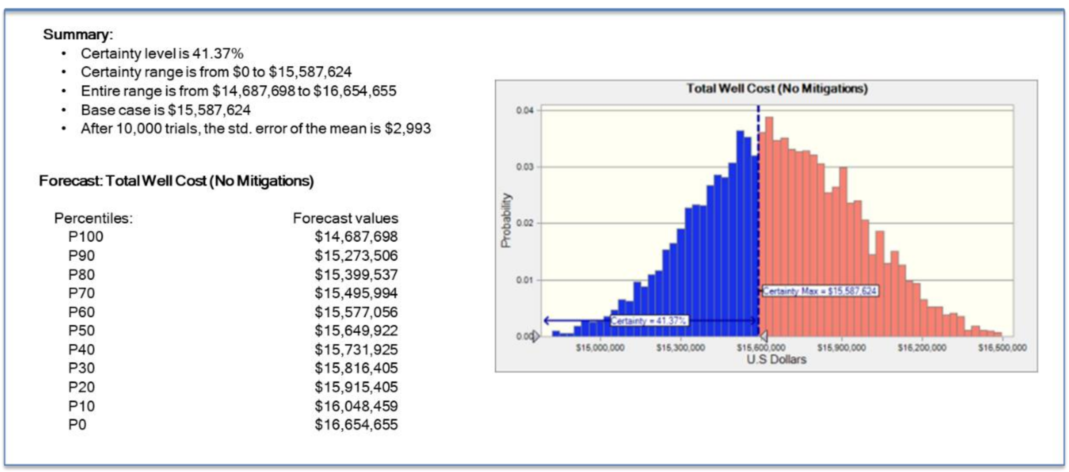

Figure 3-4 Crystal Ball Summary Report for Case 1

Case 2: Mitigated Budget (All Mitigations, All Risks Included)

Case 2 is a modification of the baseline budget case. This case was modified to account for the risks and mitigation strategies identified by the SME panel. Similarly to Case 1, the top five risks were incorporated into the Crystal Ball analysis for this case. However, the distributions for both the assumptions and the forecast values differ based on the risk profiles developed by the SME panel. As shown in Figure 5, the $POS_{well\ delivery}$ is estimated at 99.11%; this represents an increase of 57.74% compared with POS from Case 1 (41.37%). Case 2 has a baseline budget of $15,249,417. This budget is slightly lower than the Case 1 budget and accounts for time efficiencies and mitigation strategies budgets. For Case 2, the P10, P50, and P90 values correspond to $15,505,599, $15,211,077, and $14,891,252, respectively, which implies that the likelihood of the total well cost being below the baseline budget is more than 99%. Thus, this project would be considered a go if only considering the POS (not including other economic indicators, such as ROI, etc.).

Summary:

- Certainty level is 99.11%
- Certainty range is from $0 to $15,687,624
- Entire range is from $14,526,912 to $15,844,006
- Base case is $15,249,417
- After 10,000 trials, the std. error of the mean is $2,279

Forecast: Total Well Cost (Mitigations)

Percentiles:	Forecast values
P100	$14,526,912
P90	$14,891,252
P80	$14,999,305
P70	$15,080,873
P60	$15,149,756
P50	$15,211,077
P40	$15,270,967
P30	$15,332,453
P20	$15,406,628
P10	$15,505,599
P0	$15,844,006

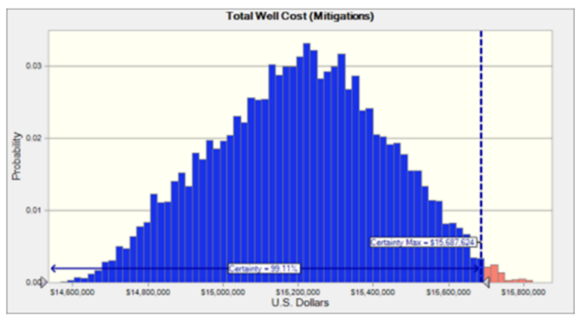

Figure 3-5 Crystal Ball Summary Report for Case 2

7. Chapter 3 Conclusions

In conclusion, estimating the probability of success (POS) is critical in deciding whether to invest in a drilling program or not. Implementing POS for the cost to create and manage a well drilling program involves estimating the probability of success, determining the appropriate level of investment required to achieve success, and monitoring and adjusting the plan as necessary.

The POS estimate should consider various factors, such as the geological and engineering challenges posed by the prospect, the quality and quantity of data available, and the level of uncertainty involved in the estimate. The appropriate level of investment required should consider the expected ROI for the drilling program, the level of risk involved, and the company's financial resources.

To maximize the chances of success, the drilling program should be designed to minimize the risks of cost overruns and delays by incorporating best practices in project management, risk management, and supply chain management. By implementing POS for the cost of creating and managing a well drilling program, companies can make informed decisions that maximize the expected ROI and minimize the risks involved.

Chapter 4 Conclusions and Future Work

1. Conclusions

This dissertation has explained the Probability of Success (POS) methodology and adapted the concepts and principles for its implementation in the Oil and Gas (O&G) industry through a real-case sample well. POS defined by this work as the probability of successfully achieving the project objectives within its program plans, can be determined as one comparable metric. Cost, schedule, performance, and risk variables are all factored into this integrated metric. This represents a significant differentiator in the industry, as a game-changer for well assessment and development by managing drilling risks and uncertainty by de-risking a set of possible viable alternatives or investment-level opportunities with a robust economic metric.

The POS approach for O&G incorporates probabilistic methods to estimate drilling costs, which organizations can use to enhance their understanding of the potential range of expenses associated with a specific investment level and the level of certainty surrounding various outcomes. This knowledge can be utilized to formulate improved strategies for managing risks and opportunities, such as developing contingency plans, mitigating risks, and allocating resources to address common issues encountered during drilling operations. Moreover, these models enable companies to identify and take advantage of opportunities that might not have been evident using traditional deterministic models.

The appropriate level of investment required should consider the expected ROI for the drilling program, the level of risk involved, and the company's financial resources. By implementing POS for the cost of creating and managing a well-drilling program, companies can make better-informed decisions that maximize the expected ROI and minimize the risks involved. Furthermore, the methodology can be adapted for multiple applications or industries in future work.

This research presented a sample risk and opportunity factors analysis for different stages of the well drilling life cycle to determine the estimated POS of achieving the project cost through probabilistic modeling. For the effects of this work, only POS cost was addressed. The goal was to provide a tool to enable more accurate and comprehensive estimates of drilling costs. This method can help companies make more informed decisions, reduce risk, and increase profitability. Future work can evaluate POS at multiple stages and factors (i.e., schedule and performance). Depending on project requirements, there could be cases where the other two factors could be of more significance than the POS Cost.

Literature and experience have shown that the top three significant effects of risk factors in oil and gas exploration wells are time overruns, cost overruns, and failure to achieve project objectives (performance). Implementing the proposed methodology would significantly increase the certainty of remaining within the initial budget for drilling operations. For the well-presented example, the certainty level would improve from 41.37% to 99.11%. This enhanced certainty assures the Approval of Expenditures (AFE) and increases the likelihood of successfully achieving the objectives of the well. Despite the seemingly insignificant drilling cost saving of $338,207 (2% of the baseline cost), it represents additional gains already reaching the well objectives. Before incorporating the mitigation strategies, there was more uncertainty regarding achieving objectives. It's important to note that the cost of implementing the mitigations and the improvements in time efficiency are considered in this calculation. The analysis results indicate that most investors typically require at least an 80% certainty level, depending on the risk and uncertainty associated with each project. For the Tornado sample well, to achieve an 80%

certainty, an estimated budget between $15,932,883 and $16,703,504 would be necessary. This implies that an additional investment of slightly over $1,000,000 would be required compared to the baseline case (without any mitigations).

2. Future Research

The Probability of Success (POS) in the oil and gas industry is a metric used to estimate the likelihood of a successful outcome in exploration and production projects. In addition to conducting POS for schedule and performance, there are three main potential areas of future research for POS in the oil and gas industry: (1) data analytics and machine learning, (2) artificial intelligence and expert systems, and (3) alternative technologies to improve POS. The following paragraph describes the areas.

Data analytics and machine learning: The oil and gas industry generates vast amounts of data, which can be leveraged to improve POS estimates. Machine learning algorithms can analyze historical data on exploration and production outcomes and identify patterns that can be used to develop predictive models for future projects.

Integration of artificial intelligence and expert systems: Expert systems could help to capture the knowledge and expertise of experienced exploration and production subject matter experts and use this information to make better decisions. Combining expert systems with artificial intelligence techniques could help to improve POS estimates by providing a more robust and comprehensive analysis of exploration and production risks.

Using alternative technologies to improve the POS: Using alternative drilling techniques (i.e., adaptive well design and Manage Pressure Drilling) can provide additional assurance when analyzing complex/challenging applications. The impact of these alternative technologies can enhance the risk and its mitigation strategies and provide additional assurance for improving POS estimations.

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Chapter 5 Appendixes

Appendix A: Chapter 3 Appendix - Drilling Days Budget Based on SME's Estimations

Example Well Sequential Step (high-level)	From (ft)	To (ft)	No mitigation			Mitigation		
			Most Likely	Best Case	Worst Case	Most Likely	Best Case	Worst Case
Prespud	0	160	14.0	14.0	14.0	14.0	14.0	14.0
Drill 17-1/2 in. Hole	160	3700	4.4	3.4	6.4	4.0	3.0	4.4
Logging	3700	3700	1.0	1.0	1.0	1.0	1.0	1.0
Run 13-5/8 in. Casing	3700	3700	2.0	2.0	2.0	2.0	1.5	2.0
Drill 12-1/4 in. Hole	3700	11500	26.0	20.0	32.0	22.0	18.0	26.0
Logging	11500	11500	2.0	2.0	2.0	2.0	2.0	2.0
Run 9-5/8 in. Casing	11500	11500	4.0	2.0	6.0	3.0	1.5	4.0
Drill 8 1/2" Hole	11500	14800	11.0	9.0	16.0	10.0	8.0	11.0
Run 7-5/8 in. Liner	14800	14800	8.0	6.0	10.0	6.0	4.0	8.0
Managed Pressure Drilling	14800	14800	4.0	4.0	4.0	4.0	3.0	4.0
Drill 6-1/2 in. Hole	14800	22000	24.0	20.0	28.0	20.0	16.0	24.0
Logging and Steem Testing	22000	22000	14.0	12.0	16.0	12.0	10.0	14.0
Run 4-1/2 in. Liner	22000	22000	2.0	2.0	4.0	2.0	1.0	2.0
Run 5-1/2 in. Tieback	22000	22000	6.0	5.0	7.0	4.0	3.0	6.0
Fracturing and Stimulation	22000	22000	15.0	12.0	20.0	13.0	10.0	15.0
Clean-up	22000	22000	5.0	5.0	5.0	4.0	3.0	5.0
Completion	22000	22000	10.0	8.0	12.0	8.0	6.0	10.0
Total Time to Drill the Well (days)			152.4	127.4	185.4	131.0	105.0	152.4

Appendix B: Chapter 3 Appendix – Crystal Ball Analysis for Individual Risks Factors

Top Five Risks Items with Higher Contribution to the Total Well Cost

Summary
- Certainty level is 42.93%
- Certainty range is from $0 to $15,587,624
- Entire range is from $15,158,833 to $16,153,945
- Base case is $15,587,624
- After 10,000 trials, the std. error of the mean is $2,071

Percentiles:	Forecast values
P100	$15,158,833
P90	$15,359,337
P80	$15,447,806
P70	$15,514,243
P60	$15,571,823
P50	$15,623,120
P40	$15,682,240
P30	$15,744,171
P20	$15,818,535
P10	$15,917,371
P0	$16,153,945

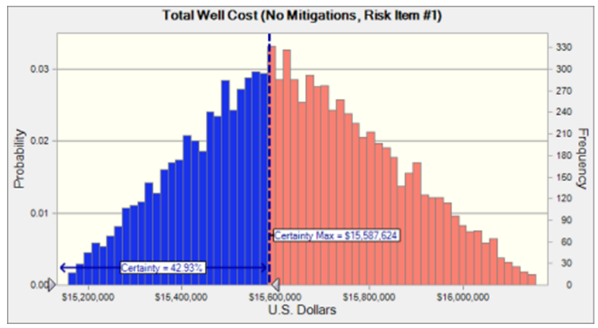

Figure 6 Crystal Ball Report for Case 1 (Risk Item #1)

Summary:
- Certainty level is 44.01%
- Certainty range is from $0 to $15,587,624
- Entire range is from $15,467,064 to $15,744,263
- Base case is $15,587,624
- After 10,000 trials, the std. error of the mean is $570

	Forecast values
P100	$15,467,064
P90	$15,524,905
P80	$15,548,264
P70	$15,566,543
P60	$15,582,247
P50	$15,596,250
P40	$15,612,042
P30	$15,629,974
P20	$15,651,020
P10	$15,678,980
P0	$15,744,263

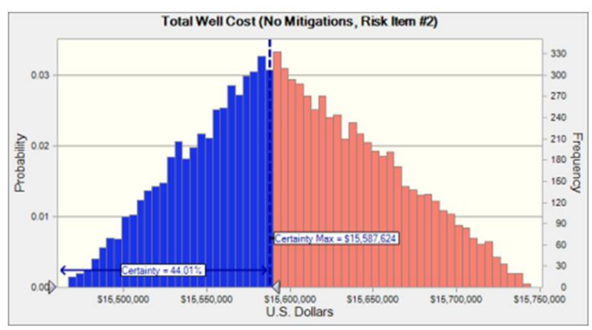

Figure 7 Crystal Ball Report for Case 1 (Risk Item #2)

Summary:

- Certainty level is 50.35%
- Certainty range is from $15,472,875 to $15,706,654
- Entire range is from $15,195,487 to $15,978,305
- Base case is $15,587,624
- After 10,000 trials, the std. error of the mean is $1,616

Percentiles:	Forecast values
P100	$15,195,487
P90	$15,369,591
P80	$15,444,364
P70	$15,500,482
P60	$15,549,614
P50	$15,589,591
P40	$15,632,567
P30	$15,679,897
P20	$15,734,877
P10	$15,808,966
P0	$15,978,305

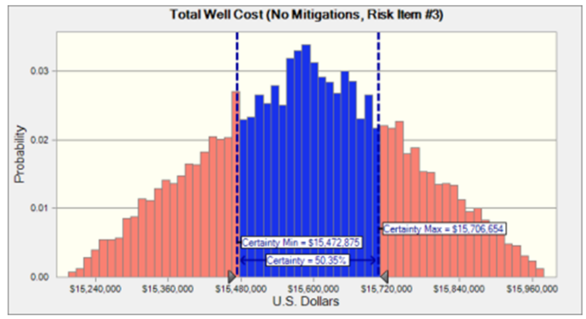

Figure 8 Crystal Ball Report for Case 1 (Risk Item #3)

Summary:

- Certainty level is 40.51%
- Certainty range is from $0 to $15,587,624
- Entire range is from $15,514,598 to $15,695,076
- Base case is $15,587,624
- After 10,000 trials, the std. error of the mean is $374

Percentiles:	Forecast values
P100	$15,514,598
P90	$15,549,930
P80	$15,565,818
P70	$15,577,512
P60	$15,587,191
P50	$15,596,753
P40	$15,607,095
P30	$15,619,254
P20	$15,633,388
P10	$15,651,432
P0	$15,695,076

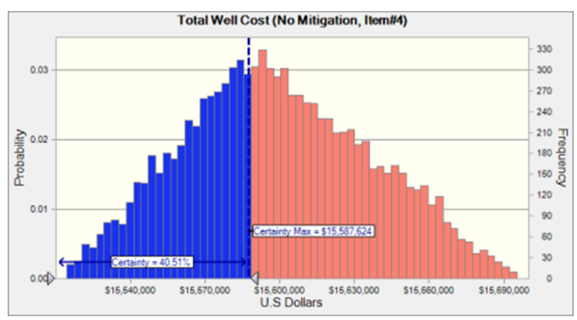

Figure 9 Crystal Ball Report for Case 1 (Risk Item #4)

Summary:

- Certainty level is 49.55%
- Certainty range is from $0 to $15,587,624
- Entire range is from $15,282,741 to $15,891,242
- Base case is $15,587,624
- After 10,000 trials, the std. error of the mean is $1,254

Percentiles:	Forecast values
P100	$15,282,741
P90	$15,418,520
P80	$15,477,805
P70	$15,520,202
P60	$15,557,414
P50	$15,588,903
P40	$15,621,253
P30	$15,659,402
P20	$15,702,232
P10	$15,759,393
P0	$15,891,242

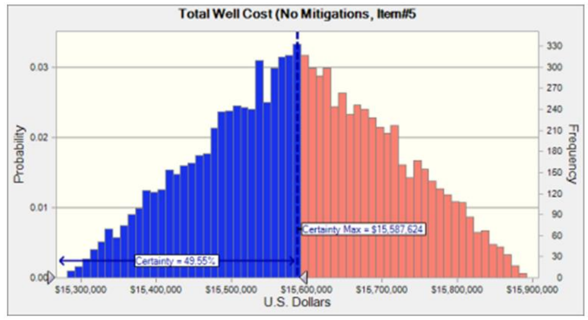

Figure 10 Crystal Ball Report for Case 1 (Risk Item #5)

Appendix C: Nomenclature and Abbreviations

Term	Definition
AFE	Approval for Expenditure
DCI	Drilling Complexity Index
EMW	Expected Monetary Value
FMECA	Failure Mode and Effect Analysis
HazID	Hazard Identification Analysis
HazOP	Hazard Operability Analysis
HPHT	High-Pressure High Temperature
MPOS	Mitigations Probability of Success
NGT	Nominal Group Technique
NPT	Non-productive time
NPV	Net Present Value
O&G	Oil and Gas
PO	Probability of Occurrence
POS	Probability of Success
RC	Risk Criteria
RML	Risks Mitigation Level
ROI	Return on Investment
ROR	Internal Rate of Return
SME	Subject Matter Experts
WDP	Well Delivery Process