Chair of Drilling and Completion Engineering

Master's Thesis

Integrated Approach to Evaluate the Drilling Solutions for Downhole Drilling Problems

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This is to my family and friends who have been
my biggest support during these years.

Affidavit

I declare in lieu of oath that I wrote this thesis and performed the associated research myself using only literature cited in this volume.

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich diese Arbeit selbständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch sonst keiner unerlaubten Hilfsmittel bedient habe.

Martin Štulec, 12 February 2020

Abstract

The role of oil and gas in the modern world is still very important. As the crude oil price is at low level, there is a constant need to improve drilling efficiency and to reduce drilling costs to the minimum. In order to do so, drilling efficiency needs to be improved. The best way to improve drilling efficiency is to evaluate different drilling methods.

The main objective of this thesis is to develop the evaluation decision-making process in evaluating preventive barriers for the downhole drilling problems. There are various solutions available at the market. One of the evaluation tools used for deciding which method would be the most cost efficient is weighted matrix method. However, this method has some limitations, as there are a lot of assumptions and uncertainties associated with the input parameters. Therefore, in order to enhance the evaluation of the decision-making process, another evaluation tool was presented. That is the probability of success method. Afterwards, these two tools were combined into an integrated approach. This was done in order to evaluate the preventive barriers for downhole drilling problems in the best possible way.

To test these developed methods in a real situation, a case study was performed to validate the approach. The main objective of a case study was an investigation of drilling operations in re-entry drilling for W-1 JR well on F-1 field. Based on drilling reports NPT (Non-Productive Time) was extracted and root causes were established. After calculating the NPT, three main problems surfaced: bit balling, high torque and drag and stuck pipe. For dealing with these problems, different methods are proposed to reduce or to mitigate encountered drilling problems in following re-entry campaign in that field area. To evaluate proposed drilling methods, an integrated approach was used, which determined that the best solution for bit balling is to change drilling hydraulics. On the other hand, the best solution for the high torque and drag and stuck pipe would be rotary steerable system.

Zusammenfassung

Die Rolle von Öl und Gas in der modernen Welt ist nach wie vor sehr wichtig. Da der Rohölpreis auf einem niedrigen Niveau liegt, besteht ein ständiger Bedarf die Bohrleistung zu verbessern und die Bohrkosten auf ein Minimum zu reduzieren. Dazu muss die Bohrleistung effizienter gemacht werden. Der beste Weg dies zu verwirklichen, ist die Bewertung verschiedener Bohrmethoden.

Das Hauptziel dieser Arbeit war die Entwicklung eines Entscheidungsprozesses zur Bewertung und der Vorbeugung von Bohrproblemen im Bohrloch. Am Markt stehen verschiedene Lösungen zur Verfügung. Eines der Werkzeuge, die im Kampf gegen dieses Problem eingesetzt werden können, ist die Methode der gewichteten Matrix. Diese Methode weist jedoch Einschränkungen auf.

Daher wurde ein weiteres Bewertungsinstrument vorgestellt, um den Bewertungsentscheidungsprozess zu verbessern. Es ist die Erfolgswahrscheinlichkeitsmethode. Anschließend wurden diese beiden Tools zu einem integrierten Ansatz kombiniert. Dies wurde durchgeführt, um die vorbeugenden Barrieren für Bohrlochprobleme bestmöglich zu bewerten.

Um die entwickelten Methoden in einer reellen Situation zu testen, wurde eine Fallstudie durchgeführt, um den Ansatz zu validieren. Das Hauptziel der Fallstudie war eine Untersuchung der Bohrvorgänge beim Wiedereintrittsbohren für das Bohrloch W-1 JR auf dem Feld F-1. Basierend auf Bohrberichten wurde die NPT (Non-Productive Time) extrahiert und die Ursachen ermittelt. Aufgrund der Hauptursache für die NPT werden verschiedene Methoden vorgeschlagen, um die aufgetretenen Bohrprobleme in der folgenden Wiedereintrittskampagne in diesem Feldbereich zu verringern. Zur Bewertung der vorgeschlagenen Bohrmethoden wurde ein integrierter Ansatz verwendet.

Acknowledgements

Primary, I would like to thank all the professors from Montanuniversität Leoben, from whome I have learned a lot during my study.

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The greatest thanks go to my family for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of writing this thesis. Without them and their support all this would not be possible. Thank you very much for everything.

And finally, one big thanks to my girlfriend Ana for being my biggest support, especially in the toughest times of my studies, when everything seemed meaningless.

Contents

Chapter 1 Introduction

The role of oil and gas in the modern world is still very important. Petroleum production is closely related to drilling methods. As the crude oil price is at a low level, there is a constant need for improving drilling efficiency and to reduce drilling costs to the minimum. Therefore, in order to do so, drilling efficiency should be improved. The best way to improve drilling efficiency is to evaluate different drilling methods.

There are various evaluation decision-making tools available at the market. One of the tools is a weighted matrix method. However, this tool has some limitations. The limitation that this tool brings is that there are a lot of parameters with uncertainties and different weighted factors that are set based on personal opinion and experience which are directly influencing the final result. In order to reduce those uncertainties and to reduce the impact of subjective weighted factors on a final decision, another evaluation decision-making tool was introduced and that was the probability of success method.

The probability of success method in the decision-making process includes only data that can be measured nor is it set on personal opinion. By introducing the probability of success method and combining these two tools into an integrated approach the uncertainties in the evaluation decision-making process are brought to the minimum. An integrated approach was developed in order to evaluate different drilling methods as a proposed solution to the occurred problems during constructing well W-1 JR from an actual case study. The thesis will be constructed in the following way.

In the beginning, chapter 2, this thesis will be reviewing drilling problems and proposed solutions to the root cause of NPT encountered in drilling well W-1 JR. There will be a short discussion of every major problem causing NPT and what could be the best solution to it. Once the problems and solutions are discussed, the next stage is to start working on these problems. As it was said before, every problem will be supported with several drilling methods. In chapter 3, risk management and different evaluation methods are explained and investigated. In order to choose which drilling method is the best, in chapter 4, the decision-making approach will be developed. The first tool that was used in the evaluation process of the best drilling methods is the weighted matrix method and the second tool was the probability of success method. These tools have some limitations; therefore, they will be combined into an integrated approach to get the best possible drilling methods to solve the root cause of NPT problems.

In chapter 5, a case study will be presented. The main objective of a case study is to:

- Analyze NPT data for the offset well
- Select key performance indicators (KPIs) for the decision-making process
- Present results for the weighted matrix evaluation method
- Present results for the probability of success method
- Combine results of weighted matrix method and probability of success method into an integrated approach
- Choose the best drilling methods for root NPT cause problems

Chapter 6 will bring the overall thinking of the thesis and a final conclusion.

Chapter 2 Drilling Problems, Causes, and Solutions

Extracting hydrocarbon from an underground reservoir is tightly connected to a lot of uncertainties. However, the key to achieving the drilling objectives is to design drilling methods based on anticipated drilling problems. The best-case scenario in drilling is to avoid situations where drilling problems arise. Some of the drilling problems are compromised with drill string failures, wellbore instability, well path control, kicks, stuck pipe, hole deviation, bit balling, well path control, lost circulation, formation damage, high torque & drag, etc.

This chapter will keep the main focus only on three of these problems: bit balling, high torque & drag and stuck pipe. The main reason for that stands behind the fact that those are the three main reasons for NPT during constructing wellbore W-1 JR. This chapter will bring detailed explanations of the problems closer to the reader by explaining the problem and its cause with proposed solutions to the problems.

Proposed solutions can be the proactive type and mitigation type. Proactive type of solutions involves preventive maintenance, which itself requires a clear understanding of the operating conditions. Mitigation type of solutions involves solutions that could only reduce the risk of loss from an undesirable event, or in this case, NPT. The main characteristic of a proactive type of solution is preplanning, while a mitigation type of solution is characterized by finding a solution while performing drilling operations.

2.1 Bit Balling

2.1.1 Introduction

Bit balling is one of the drilling operational issues that can happen anytime when drilling. Bit balling is a condition in which rock cuttings stick to the bit while drilling through Gumbo clay (i.e., Sticky clay), water-reactive clay, and shale formations [3]. This could lead to several problems such as a reduction in the rate of penetration (ROP), an increase in torque, an increase in standpipe pressure (SSP) if the nozzles are stuck as well. Bit performance in shale has been recognized as very important and studied for over 50 years. There are numerous amounts of literature on factors that affect bit performance in shale. The published research goes from understanding and characterization of the behavior of shales. In the 1960s and 1970s, research mostly kept their primary focus on bit tooth indentation and on the rock itself. With the arrival of PDC bits in the late 1970s, recent work has focused more on bit design and PDC cutter, interactions between shale and drilling fluids while trying to understand the failure behavior of shale. The most common problem associated with drilling through shale is bit balling. This problem is mostly described on the U.S. gulf coast and in a different place as the "plastic shale problem" [4].

After the rock is drilled and the cuttings are freed from the rock's surface, the radial effective stress acting on the cuttings is given by the following formula [1]:

$\sigma\, eff\, r = Pmud - Ppore - Pswelling$

where,

$Pmud$ = Uniform mud pressure, which replaces the in-situ stress as the cutting is released

$Ppore$ = Pore pressure

$Pswelling$ = Swelling pressure, which acts as a tensile force on clay platelets

Referring to van Oort (1997), when drilling shale formations, in-situ stress is released and swelling pressure generates a vacuum and attracts water from the water layers present on the bit surface. Consequently, the cuttings begin to stick to each other and to the bit surface, causing bit balling. The tendency of cuttings to adhere to the bit can also be expressed as a function of the water content of the cuttings given by Atterberg limits. As seen in Figure 1, the plastic zone can be stated as the balling zone. The initial water percentage of the shale depends on the shale type and shale clay percentage. If the shale is in a plastic zone, drilling fluid should either dehydrate cuttings to the dry zone or hydrate them to the liquid zone. Though, hydrating cuttings and moving them into the liquid zone via a dispersive mud system could change mud rheology and lead to wellbore stability problems due to their solids-dispersing tendency. Cooper and Roy (1994) showed the application of electro-osmosis to reduce bit balling by dehydrating to the dry zone.

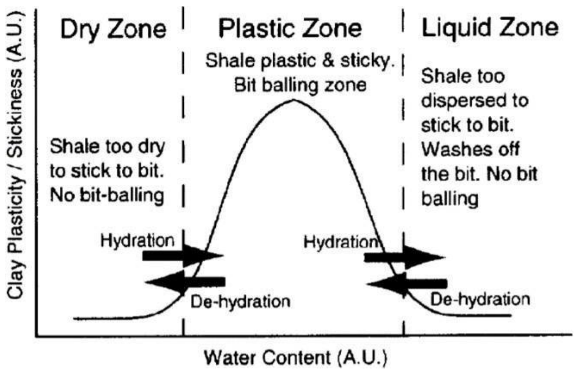


Figure 1: Atterberg Limits [4]

By taking a look into shale soil mechanics, in the initial stage shales are relatively dry clay-containing material that will adsorb water in order to reduce their internal stresses. As water is adsorbed, the shales will reach a plastic limit where the sticking tendency of shale is very high, therefore leading to all problems described above. The clay plasticity concept proposes that the rate of hydration of shale is slowed down so the cuttings could stay in a plastic state over a long period of time. [1, 2]. This plasticity state contributes towards cuttings becoming shaped onto the steel part of BHA and being plastered onto the walls of the wellbore. By using a much less inhibitive drilling fluid, shale cuttings would normally hydrate quickly and tend to be less sticky as they continue to adsorb water thus quickly passing through the plastic stage and into a liquid stage where the shale has little cohesive strength and readily disperses.

Talking about clay properties, actually, Atterberg limits are being discussed, Figure 1. Atterberg limits are defined as the liquid limit, plastic limit, and plastic index. The liquid limit (LL) is the moisture content, expressed as a percentage by the weight of the oven-dry clay. The plastic limit (PL) is the lowest moisture content, expressed as a percentage by weight of the oven-dry clay. The plastic index (PI) is the difference between the liquid limit and the plastic limit. It gives the moisture content range through which soil is considered to be plastic. Different studies show that clay and shale behavior can be summarized by stating that the liquid limit and plastic limit of shale are primarily a function of the percent clay fraction. The ratio of PL/LL was seen to increase according to clay type: (Na-montmorillonite < Illite < Kaolinite), and to the valency and hydrated ionic radius of the associated cation.

$$(Na^{+} < K^{+} < Ca^{2+} < Mg^{2+} < Fe^{3+} < Al^{3+}).$$

The presence of non-clay minerals in shale will reduce the magnitude of the PL and LL, but the ratio will remain the same. In order for cuttings accretion to occur, the following three criteria must be met [4]:

1. The shale must have sufficient moisture to be in a plastic state when getting in contact with the drilling fluid. A deformation of the shale structure can readily occur when the plastic state is achieved.
2. The surface of the shale cutting must be sticky enough to form a bond with other surfaces that it makes contact with. The "stickiness" of the shale surface can be enhanced by rapid surface water absorption from the drilling fluid, as well with some drilling fluid polymeric additives.
3. The surfaces of the cuttings must be pushed together with sufficient force to deform the clays and create a bond. This force can be both mechanically and hydraulically generated.

There are numerous different factors impacting accretion such as [5]:

- Cuttings size – In a case study, they used various sizes of shale cuttings (from 1,5 mm to 10,0 mm) and the test was conducted over the interval to 60 minutes. The effect of cuttings size on the accretion profile is shown in Figure 1. Generally, as cuttings size increases, overall levels of accretion were observed to decrease, requiring a significantly longer time for the accretion process to begin. This may be related to the cuttings surface area. A smaller cuttings size will have a greater surface area for water adsorption, and thus will tend to reach the plastic limit faster and begin to accrete faster, particularly after shorter exposure time. The lower level of accretion observed with the smallest particle size tested is believed to be a piece of the test because a more rapid disintegration of these cuttings occurred due to their higher surface area. Choosing a fluid system and drill bit combination that allows for large cuttings to be generated can be advantageous in reducing the tendency for bit balling and accretion. This requires, however, that hydraulics be optimized for removal of the cuttings from around the BHA and for hole cleaning with these larger cuttings. Poor hydraulic hole cleaning will lead to both mechanical deterioration of cuttings over time, and a longer exposure of cuttings to the drilling fluid. Both of these scenarios will contribute to an increased tendency for accretion.

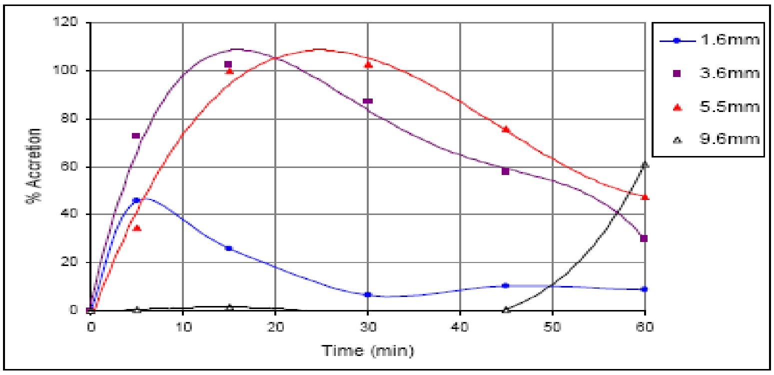


Figure 2: Effect of Cuttings Size on Accretion [5]

- Mechanical Force - The effect of mechanical force on accretion was studied by using two differing accretion bars – one solid weighing ~530.0 grams, the other hollow weighing ~140.0 grams. The results of this testing are shown in Figure 2. With a reduction in mechanical force, the accretion effect is delayed significantly and the overall extent of accretion is reduced. Accretion also eventually occurs over a wider time period even with the lower mechanical force. These results indicate that some mechanical deformation of cuttings must occur before accretion and agglomeration can take place, thus reducing the mechanical forces applied to cuttings will minimize the tendency for accretion. Good tripping practices, optimized hydraulics, and controlled ROP to keep the bit face and junk slots clean, plus stabilizing the BHA in directional wells will all minimize the mechanical forces applied. Another modification that can be made, and has been applied relatively successfully, is to modify the surface of the bit/BHA components to render them electro-negative. This will reduce the sticking tendency of the shale to the coated steel [5].

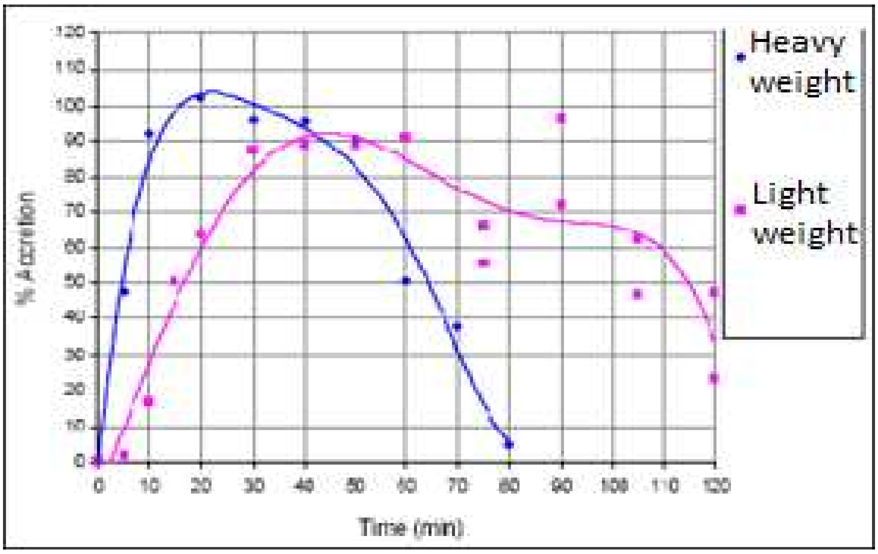


Figure 3: Effect of Mechanical Force on Accretion [5]

2.2 Methods of Bit Balling Reduction

A Polycrystalline Diamond Compact (PDC) bit drills the rock through its shear cutting action, with a great tendency to create a chip, meaning more sensitive to bit balling problem. There are several other problems connected with bit balling resulting in low drilling efficiency and high drilling costs [6] separating these methods into three main categories discussed below:

2.2.1 Modification in PDC Bit Stand Cutter Design

Zijsling et al. (1993) pointed out that the risk of bit balling can be greatly minimized by providing a large cutter standoff distance in a PDC bit. A large standoff makes big cuttings that can be transported efficiently without important contact with the body of the bit, leading to a minimization of risk to bit balling. However, this method is valid only for a specific range of drilling parameters and weakens the bit. Fear et al. (1994) in his research states that if the open face (FV) of the PDC bit is maintained above a certain number, bit balling can be limited. The FV number depends on the drilling conditions and it is higher in a water-based mud environment than in an oil-based mud system. However, Wells et al. (2008) stated that FV and junk slot area (JSA) are not the only ones responsible for the bit cleaning and gave a sequence of drilling tests that these two parameters do not associate to the bit performance. They stated that the bit balling problem in a PDC bit is more complex including multiple interacting mechanisms. They introduced two new design factors to the bit design such as junk slot shape and pinch points which should be considered in terms to reduce bit balling.

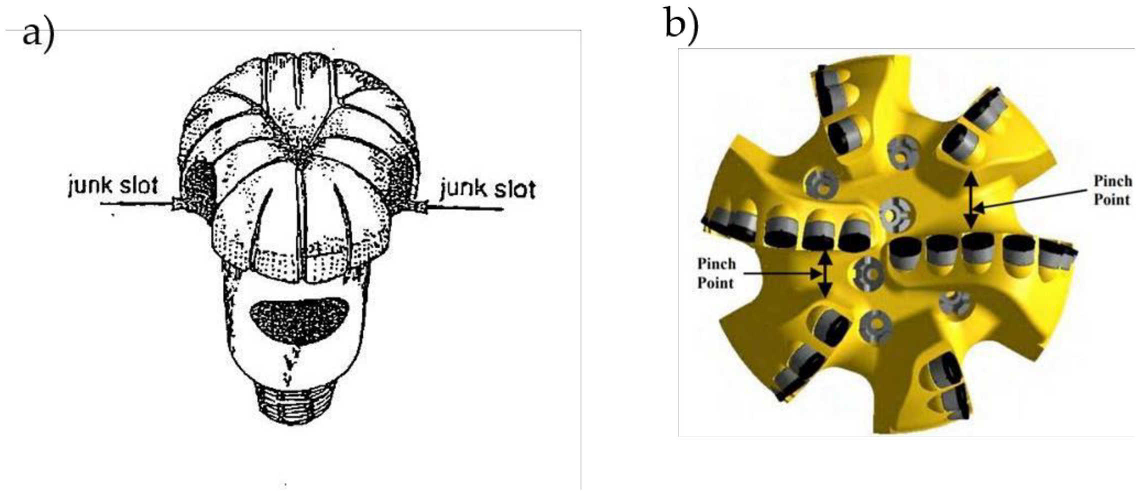


Figure 4: a) Junk slot in PDC bit; b) Pinch Point in PDC Bit [9]

Smith et al. (1996) stated that the cuttings removal is also caused by the thickness of the cuttings and the amount of generated friction. According to his research, smoothening the surface of a PDC cutter reduces the friction coefficient of the cutter and produces thin ribbon-shaped cuttings, which can be easily removed out of the hole. Consequently, the decrease in friction also reduces the produced heat amount which decreases wear resistance and improves bit life. Bland et al. (1997), conducted several drilling simulators tests, showing an increase in ROP from 3 ft/h to 150 ft/h in bit balling prone shales when these polished cutters were used in combination with WBM. Van Oort et al. (2003) claimed that the use of polished cutter bits and a ROP enhancer in WBM reduce bit balling and informed 3,75 million US $ savings on 16 drilled wells in the Gulf of Mexico. Recently, a large number of improvements on PDC polished cutters have been developed. Cooper and Roy (1994) conducted a series of laboratory-controlled drilling experiments in order to minimize the balling tendency of small PDC bits by putting a negative charge on the bit (electro-osmosis).

2.2.2 Electro-Osmosis Coating

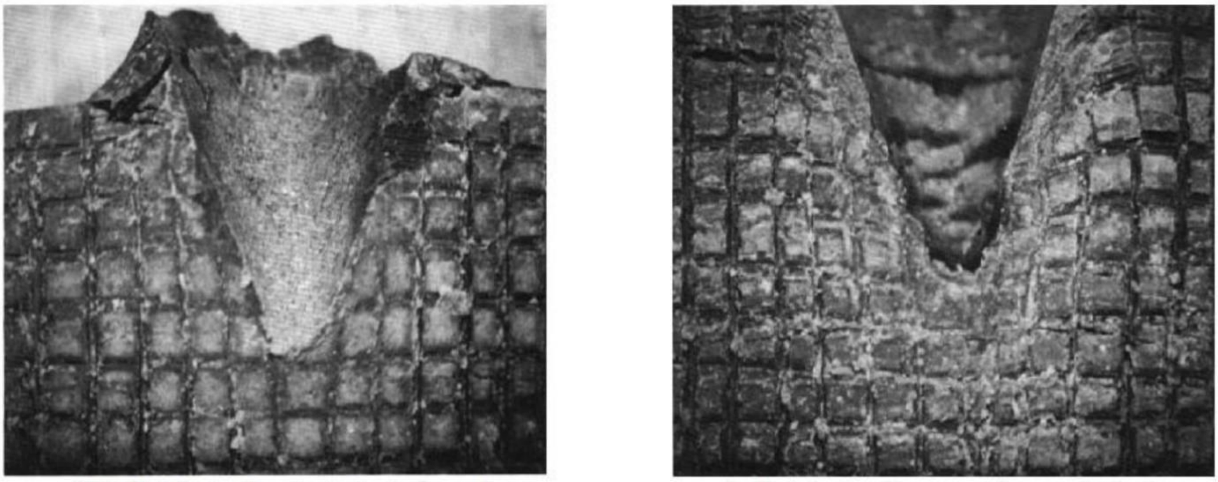
2.2.2.1 Theory of Electro-osmosis

Shale (clay) structure is composed of two basic structures, silica, and alumina. A silica structure has a tetrahedral arrangement of one silicon atom with three oxygen atoms. An alumina unit has the octahedral arrangement of one aluminum atom with six oxygen atoms. Conditional on the shale/clay type, there are different types of silica-alumina sheets arrangements. For example, in kaolinite, the basic layer is composed of one silica and one alumina sheet. In montmorillonite, one alumina sheet is in a sandwich between two silica sheets. Referring to Iwate et al. (1988), between these layers occurs isomorphous substitution. As aluminum replaces silicon in the silica sheet and magnesium replaces aluminum in the alumina sheet, these layers become negatively charged. In order to balance negative charge on the clay layer, different types of cations (Mg^{2+}+, Na^{+}, Ca^{2+}) are electrostatically attached to the clay, forming an electric double layer. As soon as electric potential is applied across the saturated clay, cations are attracted to the cathode, at the same time anions move forward to the anode. With the ion's movement, hydration shells are carried with them. Since the cations are more mobile than anions in a clay-rich shale, there is as well a net water flow towards the cathode. This flow is called electro-osmosis and its magnitude depends on the coefficient of electro-osmosis hydraulic conductivity and on the electric potential gradient

2.2.2.2 Bit Balling Reduction through Electro-Osmosis

The electro-osmosis process has been used for waste site remediation, reduction of friction, soil stabilization, shallow borehole stabilization, and petroleum production. Cooper and Roy (1991-1994) were the first to present this mechanism to reduce bit balling. They conducted a series of drilling experiments and concluded that if a drill bit is negative charged (cathode), then there is an osmotic flow of water out of shale towards the bit. This water produces a thin lubricating layer on the bit surface and this way reduces the sticking tendency of the clay. Cooper and Roy's work includes drilling parameters, testing setup and fluids specifications. Significant results from their work are:

1. In the presence of negative potential on the indenter, local extrusion was observed; however, compaction of clay occurred when the same indenter was made positive (Figure 9).



Cathodic Indenter - Local extrusion is observed **Anodic Indenter - Clay compaction around indenter**

Figure 5: Extrusion in Cathodic Indenter and Compaction in Anodic Indenter in Clay Sample (Roy et al., 1994).

2. The absolute energy required for indentation was lower for negative potential at the bit; however, it increased as the depth of the penetration increased (Figure 10)

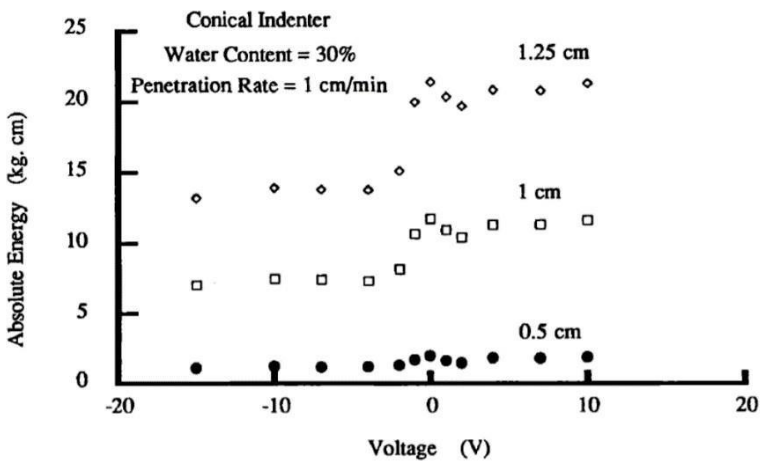


Figure 6: Absolute energy for various depths of penetration

3. As seen in Figure 11. a certain threshold negative potential (~2V) is required so the effect of electro-osmosis can be seen. Similarly, a certain maximum negative potential (~15V) exists, above which there is no effect.

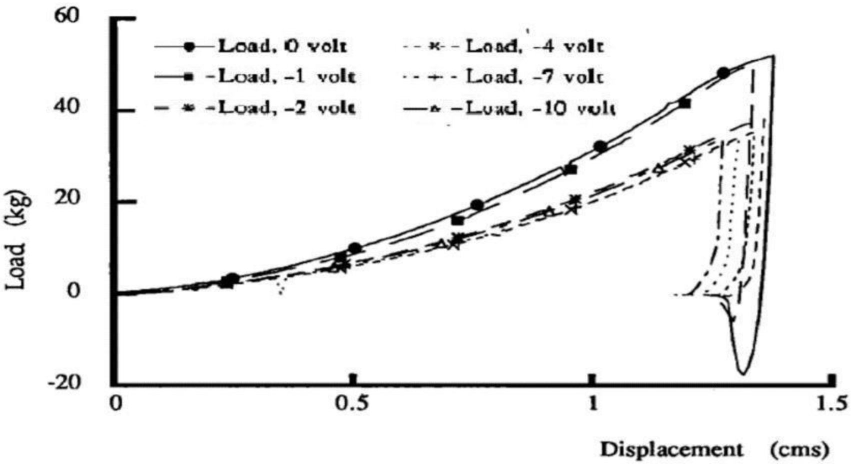


Figure 7: Load vs. Displacement Identifies a Threshold Negative Potential (Roy et al., 1994).

4. Drilling experiments done on a Wellington shale presented a nearly 100% increase in ROP in the presence of negative potential on the bit. Figure 5 shows the ROP vs. WOB data for PDC bit drilling the shale. It shows that at low WOBs there is no substantial compaction in the cuttings. The electro-osmosis process works in protection against bit balling. It shows that in low WOB's there was no bit balling, however, as the WOB increases, compaction between the cuttings increases as well and the bit started to ball. Meaning, at high WOB's, the electro-osmosis process has a bigger impact on enhancing ROP. When the negative

charge was applied, an increase in ROP from 10 ft/h to 18 ft/h at 6 000 N was registered.

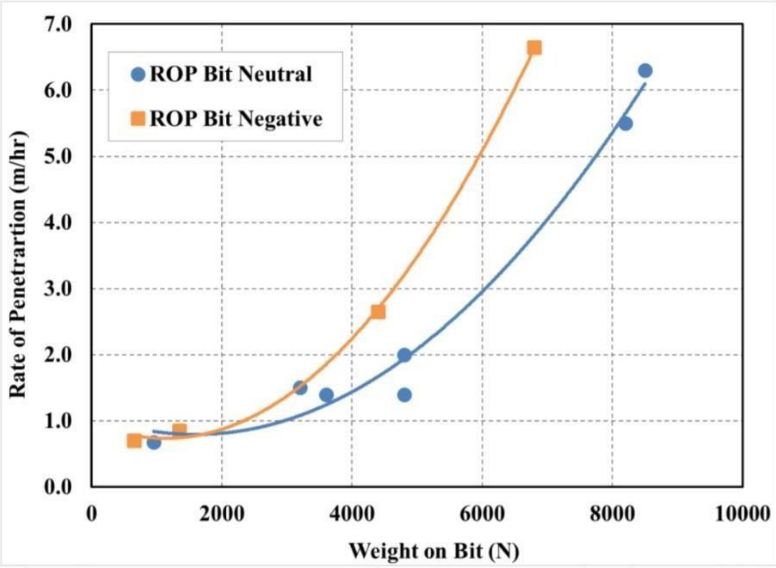


Figure 8: ROP vs. WOB Data for Neutral and Negative Bit (Cooper et al., 1994).

5. Figure 10 shows the WOB vs. weight of stuck cuttings measured on a cathodic and neutral bit. A significant decrease in cuttings weight at high WOBs is present.

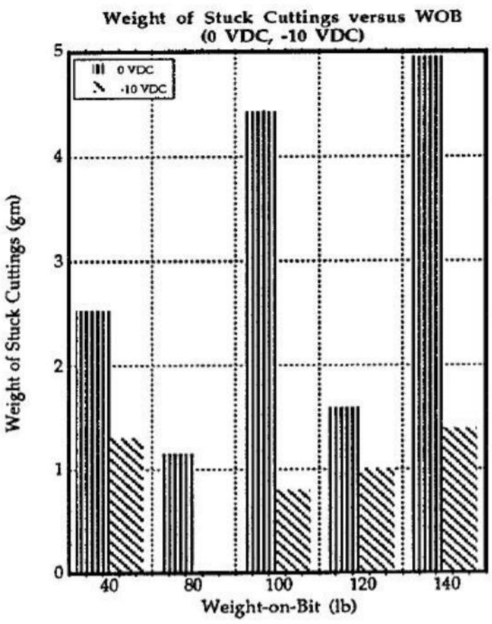


Figure 9: Weight Comparison of Stuck Cuttings between Neutral and Cathodic Bit as a Function of WOB (Hariharan et al., 1998).

2.2.3 Drilling Hydraulics Improvement

Bit hydraulics has a great influence on the drilling performance of a PDC bit. Speer (1958) straight linked the drilling efficiency of a jet bit with the hydraulic power of the mud pump. Increasing the hydraulic power of the pump (HSI) results in a fast and effective cuttings removal from the bottom-hole, meaning ROP is increased as well. Furthermore, Warren et al (1988) concluded that beyond a certain HSI, by increasing HSI, there won't be any additional influences on improving ROP. Garcia (1994) supported this idea and stated there are certain stagnant and vortex zones under the drill bit where cutting even at high HSI cannot be removed. Referring to van Oort et al. (2015), drill bit typically balls at low HSI (e.g. HSI less than 2,5). HSI is directly connected with pump strokes and flow rates, which is connected with equivalent circulating density (ECD) as well and HSI cannot be increased independently. With ECD it needs to be extra alert because if ECD exceeds fracture pressure, it can cause serious problems. Holster and Kipp (1984) have also studied the effect of hydraulics on bit balling. They resolved that gumbo shale cannot be drilled and stay without balling issue using WBM with anti-balling, nevertheless of the HSI usage.

2.2.4 Drilling Fluid Modification

Using oil-based or synthetic-based mud means there are additional costs such as cuttings treatment, waste stream processing, and compliance testing. All these factors need to be taken into consideration. Nevertheless, the higher operational costs associated with the use of invert emulsion drilling fluids can sometimes be offset because of the higher ROP and lower risks of operational problems compared to water-based drilling fluids. Over the past few years, introductions of new water-based drilling fluids have had a great impact upon the Oil and Gas industry. The new systems have a great improvement in reducing problems related to the wellbore stability, bit balling, agglomeration, and accretion of drilled cuttings. In general, two types of drilling fluid systems are used to avoid bit balling problems in shale as discussed below.

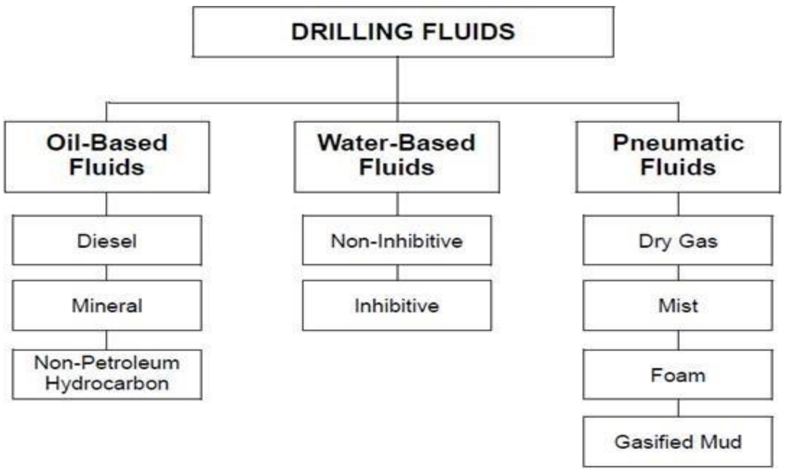


Figure 10: Drilling Fluid Classification

2.2.4.1 Water-Based Drilling Fluids with Additives and Lubricants

The usage of high-performance water-based drilling fluids is becoming more attractive to many operators that look for alternative, environmentally friendly and economically acceptable drilling fluid solutions for technically demanding drilling operations. Over the past few years, the introduction of new generations of water-based fluid drilling systems and specific additives have been positive in greatly reducing the incidence of wellbore stability problems.

The effects of varying chemistry and concentrations of specific drilling fluid additives on accretion have been extensively investigated. These investigations have already contributed to the development of some novel chemical solutions to reduce cuttings accretion and agglomeration. Two examples are the use of encapsulating polymers (typically high-molecular-weight charged polymers that can envelop shale cuttings to prevent dispersion of the shale and hinder uptake of water into the shale) and the use of lubricants (materials typically used to decrease the coefficient of friction of a drilling fluid and often used to alleviate bit balling and accretion). Figure 11 shows the comparative accretion profiles of an inhibitive water-based drilling fluid treated with differing types of encapsulating polymer. Polymer A is a conventional partially hydrolyzed polyacrylamide (PHPA) polymer that is anionically charged. Polymer C is a catatonically modified acrylamide-based synthetic polymer. Polymer D is a new synthetic polymer having a mild cationic charge. From this data, it is shown that choosing the correct encapsulating polymer can have a significant effect on the accretion of shales. The new polymer developed (polymer D) shows a significant reduction in the maximum amount of shale accreted [5].

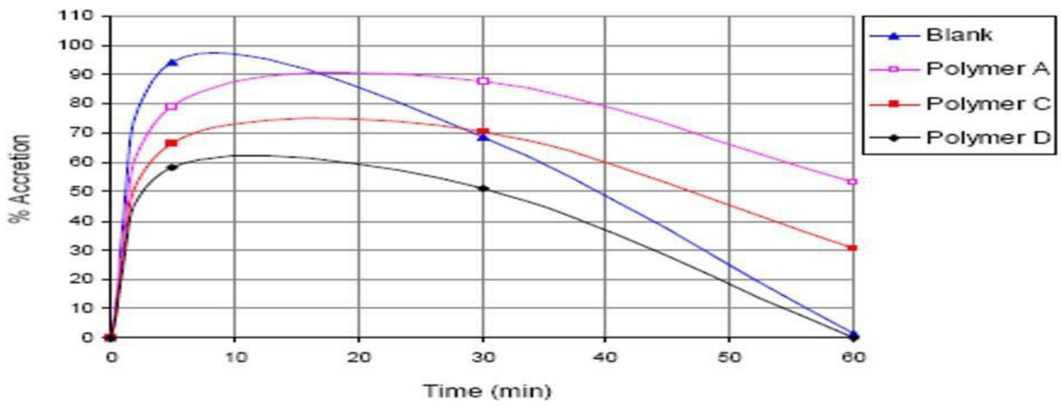


Figure 11: Accretion profiles of differing encapsulating polymers [5]

Figure 7 shows the extent of accretion observed after 30 minutes with the addition of a 3% volume of a number of different lubricants to the drilling fluid system.

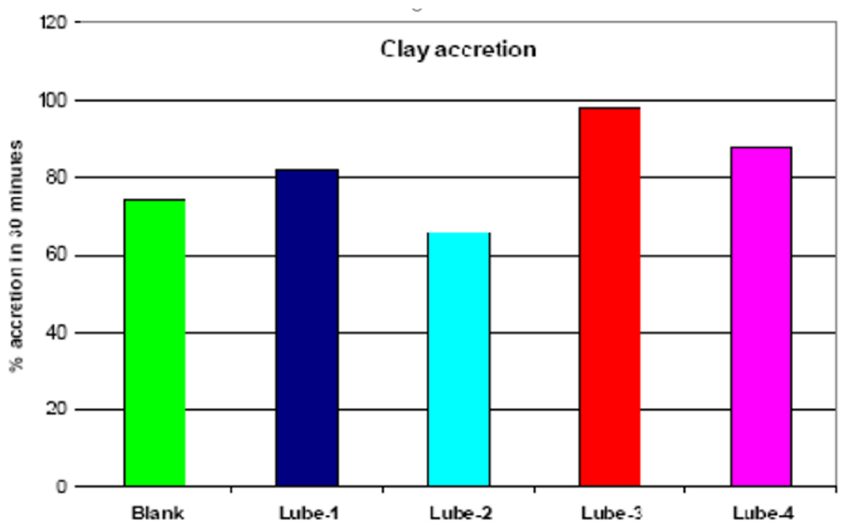


Figure 12: Accretion after 30 minutes for various lubricants [5]

As shown in the graph, the use of lubricants does not always improve shale accretion. The choice of picking the wrong lubricant can lead to a worsening of any potential accretion. Accretion tendency is visible with lubricants 2, 3 and 4. These lubricants were tested based on the traditional acid ester chemistry used in common lubricants. New additives have been developed over the past few years in order to decrease the effect of bit balling, accretion and poor ROP when drilling with inhibitive water-based drilling fluids. Usually, those kinds of additives are composed of a blend of lubricants, surfactants and wetting agents. These materials, in ideal conditions, will apply a non-aqueous wetting to the surfaces of steel and shale also contributing to chemically hindering the uptake of water by a shale's surface.

2.2.4.2 Field Testing

In order to evaluate the performance of an anticrete additives designed for general use in water-based drilling fluids, a field trial was performed. The test was done in the South Pelto, the Gulf of Mexico, where they had a lot of information available from offset wells drilled with water/Ligno-Sulphonate, Diesel invert emulsion, and Sodium Chloride/-PHPA fluids. For this test a Sodium Chloride/PHA mud was used, into which the anticrete additive was added. The offset wells drilled with water-based fluids had been drilled with significantly lower ROP's than the invert emulsion. This was believed to be because of bit balling, with some signs of shale accreted to BHA components. The 8 ½" section was drilled using a roller cone bit.

2.2.4.3 Oil-Based Mud (OBM)

In oil-based drilling fluid systems, the continuous phase is composed of liquid hydrocarbon. In this system, the movement of the water into the shale is restrained due to the high osmotic pressure of the continuous phase. In this situation, a lubricating layer is formed on the bit surface in order to minimize bit balling problems. Also, OBM does not allow mud pressure attack into the formation, meaning it is a good solution for borehole stability. The OBM system is the best solution to drill fast, stable and clean holes in a shale. Still, some problems are also related to OBM. Van Oort et al. (2015) pointed out a few of these problems:

- Strict environmental regulations
- Higher per barrel costs
- Difficulties in obtaining high-quality resistivity logs
- Oil emulsion blocks in tight gas sands
- Sensitivity to severe lost circulation
- Incompatibility with cement, resulting in cement problems
- High waste-disposal costs

2.3 High Torque and Drag

2.3.1 Overview

With the global trend moving toward ultra-extended reach wells and complex geometry wells, we can no more ignore the drilling limitations caused by high torque and drag forces. Extreme torque and drag values, especially unplanned, can be damaging to the drilling operations. Over the years, engineers have developed several ways to challenge the drilling limitations caused by high torque and drag value in order to drill further and deeper. In this chapter, a discussion about torque and drag together with methods on how to reduce them will be guided.

2.3.2 Torque

Torque is the moment required to rotate the pipe. (Figure 13.) The moment is used to overcome the rotational force on the bit and in the well. When the torque is lost, less torque is available for the bit to destroy the rock surface. High torque and drag values normally occur together. In a perfect vertical well, the torque loss in a drill string would be zero, except for a small value for loss due to viscous force from the drilling fluid system. In a deviated well the torque loss could be a big number, becoming a huge problem and a limiting factor in drilling a stable borehole. Torque is directly proportional to the coefficient of friction, radius of the drill string and the normal force acting against the borehole. With large normal forces created at the drill string/ wellbore contact, high torque is generated. These forces can exceed the rig or drill pipe capacity with failure to reach the final depth as the inevitable result [16].

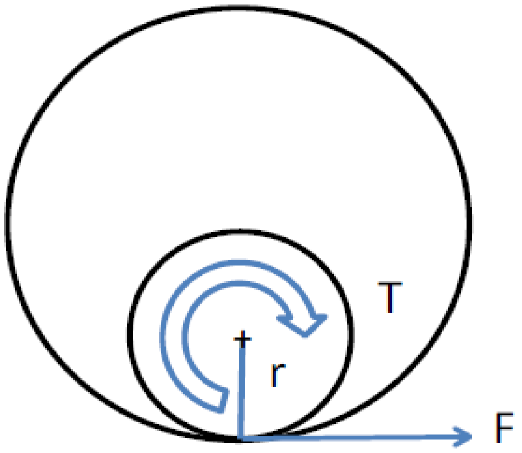


Figure 13: Torque [16]

2.3.3 Drag

Drag is the force difference between the force required to move the drill string up or down in the well bore and the free rotating weight. (Figure 14.). The pick-up drag force is usually bigger than the free rotating weight. On the other hand, the slack-off drag force is usually smaller than the free rotating weight. Drag force is used to overcome the axial friction in the well. This is a phenomenon related to deviated wells. Axial drag can lead to many difficulties, including the inability to run drill string to the bottom of the hole, or the inability to get a required weight to downhole tools.

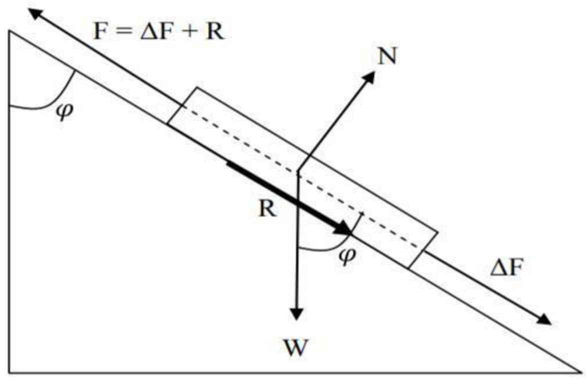


Figure 14: Drag [16]

2.3.3.1 Sources of Excessive Torque and Drag

The main causes of excessive torque and drag are hole instability, key seating, differential sticking and poor well bore friction [16].

1. **Hole Instability:** Hole instability such as a tight hole, swelling and sloughing shale increase the torque and drag due to change of the original shape and size of the hole which increases friction between the wellbore and the drill string. Interaction between the drilling fluid and the formation influences the friction and results in an erosion of a well. A loss of circulation has an influence on the friction as it gives rise to friction in the wellbore due to the lack of lubrication.
2. **Key Seating:** Key seating is the well condition in which a tube of small diameter is worn into the side of a borehole with a larger diameter (Figure 15.). It is generally a result of severe hole direction deviations, such as a high dogleg or a hard formation ledge left in soft formations that erode and that way enlarge with time. The larger diameter tools such as stabilizers, tool joints, and drill collars are not able to pass through the key seating and they become stuck, which leads to problems associated with high torque and drag. The preventive method is to enlarge spots where a key seating is created so that larger diameters tools can pass freely.

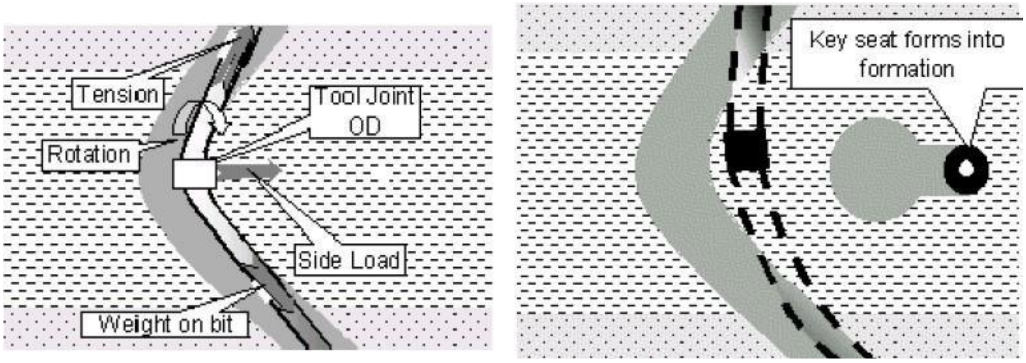


Figure 15: Key Seating [25]

3. **Differential Sticking:** Differential sticking happens when high wellbore pressure causes a high contact force of the drill string against the wall of low formation pressure, mostly in high permeable zones. Differential pressure is created when the hydrostatic pressure of a drilling fluid acts on the outside contact area of the drill string is greater than the formation fluid pressure and results in a sticking force. In that case, the drill string will be difficult to rotate or move axially, which increases torque and drag.

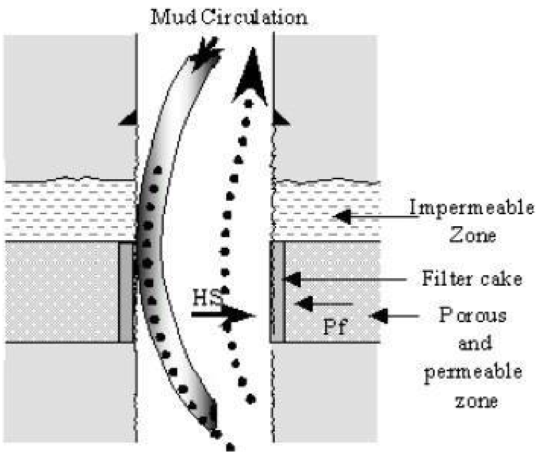


Figure 16: Differential Sticking [25]

4. **Poor Hole Cleaning:** Hole cleaning is a major problem while drilling a well. Poor cleaning can cause improper cuttings transport, meaning an accumulation of cuttings in the wellbore and high angle section of cuttings bed are generated. These conditions increase the friction increase the friction in the wellbore and cause high torque and drag. An increase in equivalent circulating density can show improper hole cleaning (Figure 17).

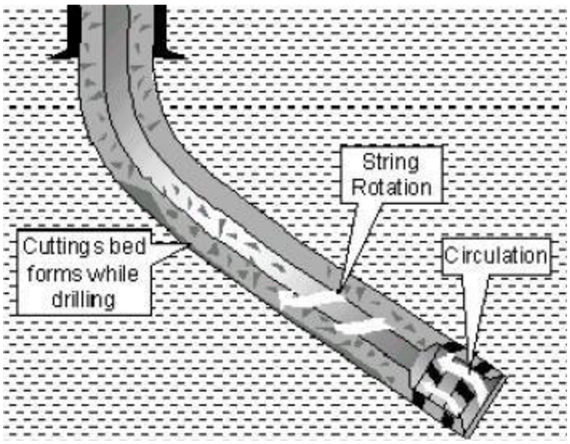


Figure 17: Cuttings Bed due to Poor Hole Cleaning [25]

5. **Wellbore Friction:** Friction happens due to the interaction between the drill string and the wellbore as frictional forces are produced against the direction of the movement. Contact friction is when two relative smooth solid bodies slide into each other. It is independent of the contact are and the sliding speed of the two bodies. Still, the friction force will be related to the contact force of which the surfaces are pressed together. A friction coefficient μ, is equal to the ratio of a normal force to the friction force. It is a dimensionless scalar value. Friction factors can be estimated for cased and open holes according to the previous drilling experiences in offset wells. [16].

2.3.3.2 Methods of Torque and Drag Reduction

In order to mitigate torque and drag forces, engineers have developed different methods that have improved over the years. Technically speaking, there is no way for torque and drag to be eliminated completely because frictionless surfaces do not exist. The variables which are partof torque and drag analysis are shown below. Drag is proportional to the normal force, tubular movement and the coefficient of friction **(Equation 1)**. Torque is proportional to the normal force, tubular movement, coefficient of friction and radius about which torque is generated. **(Equation 2)**. Reducing any of these factors will reduce the torque and drag in the end. The application of such methods can be very important in order to reach the final depth. Different methods are listed below [16].

$$F_{drag} = F_N * \mu * \frac{STS}{SVS} \qquad \text{[Eq. 1]}$$

$$F_{torque} = F_N * r_{torque} * \mu * \frac{SAES}{SVS} \qquad \text{[Eq. 2]}$$

In the following text, the main focus will be kept on the different Torque and Drag reduction categories shown below.

1. Reducing the normal forces
2. Reducing the coefficient of friction

3. Increasing dynamic vs. static conditions
4. Increasing system capabilities

The lead paragraphs in each section explain the different classes of torque and drag reduction and the methods that fall in each class.

1. Reducing the Normal Forces:

The normal force is a force opposing the side load against the borehole in the perpendicular direction. If we assume the tubulars are centered in the hole and no contact is made between the hole and the tubular, the normal force in a purely vertical section of the borehole is then zero. However, no vertical section is made without doglegs. Sections of the string will touch the borehole, therefore the normal force or the side weight in the vertical section will be very small, but never will it be zero. Figure 18 shows the different sections of the tubular string and the mentioned side weight.

Minimizing the normal force will result in a more efficient weight transfer to the bit and in less drag. Methods that reduce the normal force include wisely designing a well path and using lower weight string such as aluminum drill pipe in the lateral section of the well.

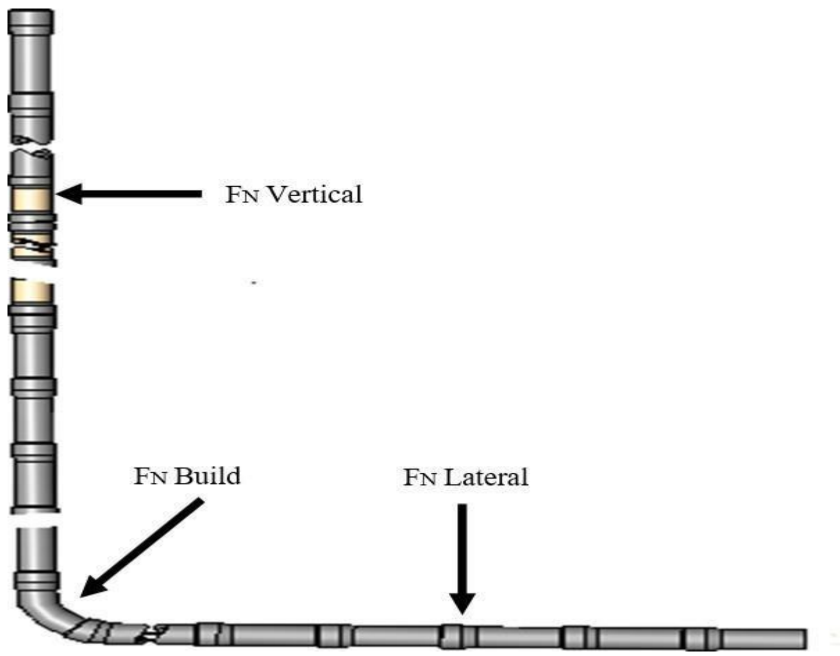


Figure 18: Tubular String Components [16]

Tortuosity reduction helps in torque and drag reduction while drilling. The use of RSS technology is recommended for making smooth wellbore. In an agreement with geologists, finding compromises may be very beneficial, as even minor adjustments to the final target could reduce the torque and drag [20]. Reducing DLS in a buildup, drop off and bends can expressively reduce torque and drag especially at the top of the well where tension forces are the biggest.

2. Reducing the Coefficient of Friction

In the oil & gas industry, many attempts have been made to reduce the coefficient of friction in order to reduce torque and drag. The coefficient of friction is a measure of the degree of resistance of the two elements sliding against each other. In a downhole operation, the coefficient of friction refers to the metal to the metal contact or metal to the formation contact between the drill string and the casing or the open hole. In a normal condition, the modeled cased hole coefficient of friction in a water-based mud will be 0.25, while the coefficient of friction in an open hole will be 0.35. Depending on the well conditions, the rate of penetration, the formation, and the mud system selection, the friction factor can be changed at the discrepancy of the user. Even a 10.00% reduction in the coefficient of friction will significantly increase the chance to reach the final depth. Some of the ways the oil industry has lowered the coefficient of friction are listed below.

Lubricants

Lubricants are additives to the drilling fluid system that have been used to reduce torque and drag forces. In the oil & gas industry, lubricants are mostly used in combination with drilling mud that cools the bit and lubricates the string. Over the years, various different additives have been tested to optimize the lubrication by maximizing the reduction of the coefficient of friction. Lubricants can reduce the coefficient of friction up to 40.00%. Nevertheless, it is very important to fully understand that tests that show an 80.00% reduction in the coefficient of friction often result in a 5.00 – 15.00% reduction of torque and drag in field conditions.

Field experiences are different, from successes to failures. In the Gulf of Mexico, a drilling company had high torque that threatened to exceed the makeup torque of their drill pipes in 2008. They switched the complete drilling fluid system in order to lower the surface torque 5.00 – 15.00% but have ended in torque increase by 7.00%.

A drilling company from Russia found out that a lubricant with a 90.00% reduction in the coefficient of friction in lab conditions will reduce torque by an average of 10.00% in a field condition [16].

Hole Cleaning

In wells where hole cleaning is inappropriate, unwanted cuttings in the hole decrease the potential for a drill string to move and rotate. It can increase the rate of wear of downhole tools as well. Cuttings are most probable to accumulate up in the high build section. This makes the removal of the cuttings from the hole awfully difficult. Thus, pipe rotation is actually a very important parameter to consider in order to ensure good hole cleaning. Increasing the RPM of the drill string will result in better cutting transportation out of the hole. Increasing the mud flow lets the cuttings to be suspended and carried up to the surface. High viscosity pills, also known as sweeps are used to reduce cuttings beds.

The oil & gas industry has industrialized mechanical tools that can maximize hole cleaning in the deviated section of the well while drilling by taking cuttings up into the high flow are of highly deviated wellbore sections. Proper hole cleaning can eliminate problems with cutting build in a wellbore and excessive torque and drag. The prime profits of the mechanical hole cleaning tools are the increase in cleaning efficiency, operational safety, time-saving and the increase in wellbore stability and quality. The tools have specially designed grooves in the tubular that heave the cuttings upward when rotating the drill string. The grooved upset shovel the cuttings and heaves them upward. It rises the recirculation of cuttings, resulting in more effective cuttings removal. The tools can improve hole cleaning efficiency up to 60.00% and torque and drag reduction up to 30.00% [16].

Co-Polymer Beads

This is a mechanical way to reduce the coefficient of friction. Co-polymer beads are implanted between the drill string and bore hole to reduce the coefficient of friction. It does not distress the chemical characteristics of a drilling fluid system. The size of these beds ranges from fine grade to coarse grade classes. As a replacement for having metal to metal contact during the drilling, the drill string slides down the well bore, rolling on the beds.

The biggest problem using beads is the major solid build up if the beds are not properly removed. Therefore, beds must be recovered and recycled. This can be accomplished by circulating drilling mud to the surface [16].

Mechanical Friction Reduction Subs

Mechanical friction reduction subs have been tested and proven in a fight against friction reduction. Practices of mechanical reduction tools have shown to be very effective in several wells in the Gulf of Mexico [20]. Different types of mechanical reduction tools exist in the industry. Some of them consist of mechanical rollers or a sleeve on bearings, which then becomes the effective contact surface. The low friction in a smooth bearing relative to rough steel against the rough steel decreases the torque and drag meaningfully. The mechanical reduction friction subs are normally placed one pre in the sections of the well that feels the highest side force. In the wells where torque and drag become higher, mechanical reduction subs have been deployed as a contingency and halted drilling before reaching final depth. The use of these mechanical friction reduction subs has reduced torque and drag in the way to continue drilling (Long et al. 2009). Although these mechanical friction reduction tools have larger OD and they are heavier than drill pipe, which would in normal conditions give higher torque and drag, the final effect is compensated by the reduction of friction that these tools deliver. Another advantage is that casing wear is reduced by the use of these tools.

3. Increasing Dynamic vs. Static Friction Conditions

Dynamic friction is lower than static friction. Different various methods are used in order to increase dynamic friction condition vs static friction, rotating pipe while tripping in as well.

Pressure Pulse Friction Reducing Tool (PPFRT)

A PPFRT is a type of mechanical friction reduction tool that sends a vibration into the string to break static friction. It oscillates in a string and makes axial movement in it. A PPFRT can meaningfully improve weight transfer to the bit and reduce the friction during drilling. This way rate of penetration is improved and anti-stalling for rotary steerable systems as well. A PPDRTs are particularly helpful in non-rotating scenarios, such as slide drilling. A PPFRTs vibrate and excite the drill string to decrease friction. Thus, in return improves the ROP by more efficient power transfer to the bit.

A PPFRTs use one of the earliest torque and drag reduction methods. There are three main components that structure a PPFRT: the power section, the bearing system, and the pulsing system. When fluid is pumped into the drill string through the power section, the rotor is making rotation in the stator and makes a flow path that lets the pulsing valve assembly to produce a series of fast pressure pulse oscillations that result in axial movement in the string. A PPFRT also induces a series of vibrations in the axial direction, together serves as a means to break the static friction produced by contact between the formation and the drill string.

4. Increasing System Capabilities

Another big impact on the extension of drilling deeper holes has been an increase in the size of drilling rigs and the strength of string components. Instead of trying to reduce the friction factor, drilling rigs and string components have increased in strength and size to withstand more demanding conditions. With more challenging wells, increased drag and torque forces have often been met by increasing the whole system capabilities rather than trying to reduce the friction during the drilling operations

Tubular Grade

S-135 strength grade pipe has been standardized in the oil and gas drilling operations for many years. Recent innovations include the development of 150.00 kpsi and higher strength of drill pipes. E, G and X drilling pipes with 75.00 to 105.00 kpsi yields have been used for sour service operations, but numerous will be soon replaced with sour service drill pipe that has a minimum yield strength of 120.00 kpsi.

Rotary Shoulder Connections

Different advancements have been made in rotary shoulder connections in order to ensure that the tubular connections can withstand high torque and drag scenarios. As more high torque and drag complicated wells have been drilled, it has become essential to improve upon the conventional connections that API verified in the 1960s. The biggest innovation was the development of double-shouldered connections, which have allowed drill strings to grip much larger amounts of torque. More than a few generations of double shouldered connections have been developed in the past few years, with the most recent using a double start threat to increase torque capacity and reduce makeup time during long tripping operations.

Rig Capabilities

Bigger, more powerful drilling rigs are becoming more common in the oil and gas industry. Top drives have moved in various areas from strict offshore rigs to include land rigs. The most challenging wells in today’s oil and gas industry use the biggest, most powerful rigs in existence, with hookload and torque capabilities that exceed those of ten years earlier by far.

Rotary Steerable Systems

A wellbore drilled with a mud motor with a bent sub in practice has greater tortuosity than with an RSS technology. This is due to the steering principles of such tools. Directional drillers are getting the desired DLS by switching from rotary drilling to sliding drilling as needed. Rotary drilling mode creates smaller holes than a sliding mode. Drilling with a mud motor will create bigger holes than drilling with an RSS technology. In sliding mode, a high DLS is accomplished to correct for the direction achieved by rotary drilling, this is because of a combination of gravity and centralizer placement. The reason why mud motors create much more tortuosity than an RSS stands behind this continued alteration. Adding a mud motor to the RSS will increase the rate of penetration, while RPM at the surface will be reduced to the minimum values and in this way will reduce the torque. Using RSS technology in combination with integrated mud motor will reduce surface torque as compared to a conventional RSS [19, 20].

2.4 Stuck Pipe

2.4.1 Introduction

Stuck pipe is one of the most common problems met in drilling. This chapter will briefly explain the different mechanisms and how to prevent stuck-pipe. When the pipe is stuck, means that the drill string cannot be moved and pulled out of the hole without damaging the pipe or exceeding the maximum hook load of the rig. It results in NPT due to the requirement to free the drill string. If the attempts to free the drill string are unsuccessful, then fishing operations are required which also could in the end also result negative. The drill pipe gets stuck due to different situations. From the industry experience the most frequent are:

- Differential sticking
- Formation-related sticking
- Mechanical sticking

In the following text stuck pipe mechanisms will be explained more into details.

2.4.2 Differential Sticking

Differential sticking happens in permeable zones where drill pipes, drill collars or casing get pressed into the mud-caked and pinned to the borehole wall by the mud's hydrostatic pressure and lower formation pressure difference. The pipe is held in the cake by a difference in pressure between the hydrostatic pressure of the drilling fluid and the pore pressure of the permeable zone. The force essential to pull the pipe can exceed the pipe strength. When the differential pressure between the mud and formation is big enough, the drill string is pushed towards the borehole wall, (Figure 19) reaching enough pinning force to impede rotation and pulling the string.

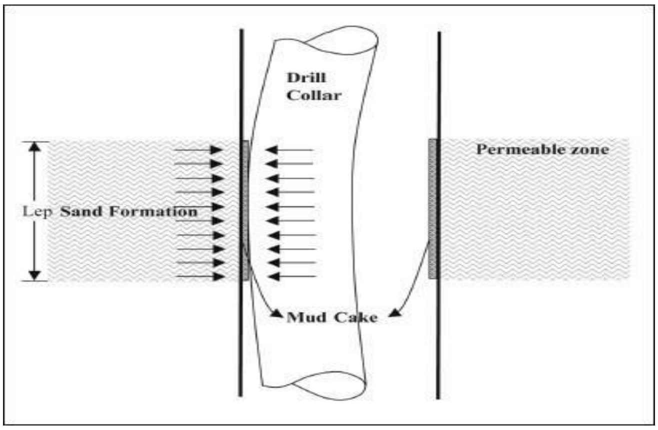


Figure 19: Differential Pressure Stuck Pipe [25]

This state occurs when the pipe is not rotating. The dimension of the pining force is related to differential pressure, formation permeability, zone thickness, thickness and slickness of filter cake, hole and pipe size and time length the drill string remains stuck against the formation. As it can be concluded, the scale of the issue can be variable. [23]

$\Delta F = (H_s - p_f) + {}^*A * f$

Where:

ΔF – pining force

Hs – hydrostatic pressure of mud

P_f – formation pressure

f- friction factor, allows for variation in the magnitude of contact between steel and filter cakes of different composition

A – contact area

A= h * t

Where:

h- thickness of permeable zone

t- thickness of filter cake

What can be seen from the formulas is that the magnitude of the differential force is very sensitive to changes in the values of friction factor and the contact area between the drill string and the borehole, because of the fact both are time-dependent. [24] In other words, when the pipe stays stationary in the well, the filter cake is becoming thicker. Furthermore, during a time, the friction factor increases with a consequence of more water being filtered out of the filter cake. Additionally, the differential force is dependent on differential pressure. Some indicators of differential sticking stuck pipe while drilling permeable zones are:

- Increase in torque and drag
- Drilling fluid circulation is not interrupted

- Inability to reciprocate the drill string

2.4.2.1 Formation Related

Formation related sticking happens when unstable formation squeezes the drill string. This happens in the presence of swelling clays, unconsolidated rocks and flowing formations such as plastic shales and salt. In this chapter, we will discuss the possible formation related failures that would have bound the drill string.

Swelling Clays Sticking

When drill bit reaches unstable shales or phyllites that in presence of water, tend to swell, sticking failure can be produced due to reduction in the diameter, tightening the hole and gripping the drill string [26]. The reason of swelling is the presence of clays in their structure that reacts with water, hydration process which results in formation swelling. All swelling clays are a potential cause of stuck pipe due to their high concertation with montmorillonite or smectite that has a big tendency to accumulate water and to increase in volume. If the formation wall does not reach the drill string, it also reduces the annular space and, in that way, restricts proper hole cleaning. The utilization of a water-based drilling fluid system in reactive formations can cause clays hydration, creating a bumpy borehole wall (Figure 20). This bumpy borehole wall could grip the strings, or its particles could pack off BHA.

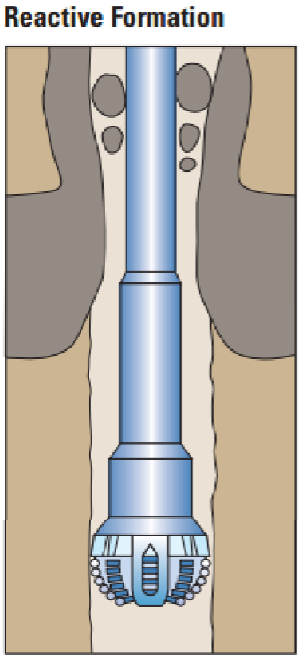


Figure 20: Swelling Clay [26]

Unconsolidated Formations

This type of failure most commonly happens in the zones where the hydrostatic mud pressure alone cannot support the formation. When this happens, the formation material often falls into the hole and pack off around the drill string (Figure 4). The formations that are frequently involved in this type of failure are unconsolidated sands, bolders, gravels, and conglomerates. Especially if water-based mud is used as a drilling fluid. To drill these formations, the drilling fluid should provide a respectable-quality mud filter cake to consolidate the formations and prevent washouts, an excessive hole enlargement caused by erosion due to the low cohesion of the drilled material or by the high mudflow intensity near the drill bit. This problem is closely connected with the mud saturation. Problems will also appear if insufficient filter cake is deposited on loose, unconsolidated sand.

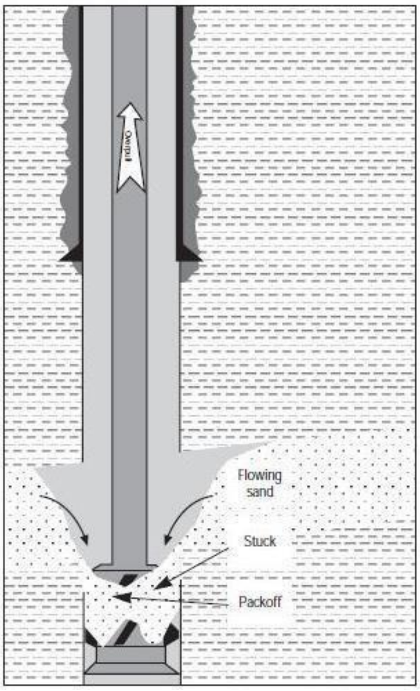


Figure 21: Pack off caused by unconsolidated formations [25]

Unstable Formations

Before the formation is drilled, the rock strength is in equilibrium with the in-situ rock stress. While the borehole is being drilled, the balance between the rock strength and in-situ stress starts to being distressed. This perturbation and the additional action of the mud can donate to the out of order of equilibrium. These factors can donate to potentially cause an instability problem in the walls of the borehole.

The hole collapse in mechanical failures is mostly connected with an increment of the borehole diameter of the hole because of brittle failure and caving of the wellbore wall. If the cuttings are not transported, it is a potential source of stuck pipe (Figure 21). This generally occurs in brittle rocks, but it also can happen in weak rock.

In general, brittle formations are responsible for this type of failure. These types of formations cause brittle shear failure producing cavings. The shape of produced cavings will strongly depend on the failure mode that is acting. It can be shear or radial tensile failure mode. Shear failure might occur when the shear stress is maximum at the borehole wall and the failure will be started when it is maximized. Such situations can be found when pressure increases and effective stress suddenly decreases near the wellbore wall. In contrast, tensile failure happens when the tangential stress is equal to the tensile strength of the rock, which happens more often in sedimentary and unconsolidated rock.

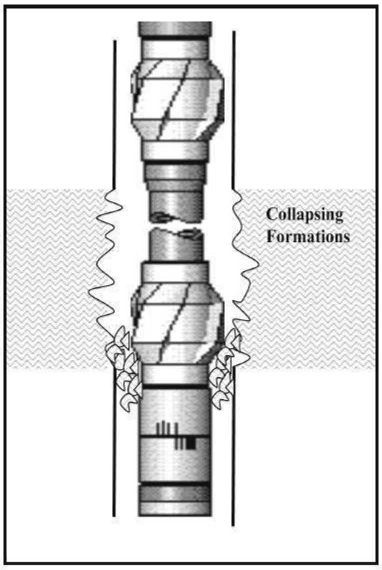


Figure 22: Borehole wall collapse caused by mechanical failure. [28]

Effect of Bedding Plane and Lamination

The dipping angles of the formations is an important criterion to analyze the potential instability while the borehole is being drilled. In order to avoid problematic drilling, the orientation of the weak planes of the drilled formations should be taken into account. Explored results in wellbores drilled 45º to weak bedding planes in artificial shale formations show the potential instability of drilling at this angle [29], (Figure 23).

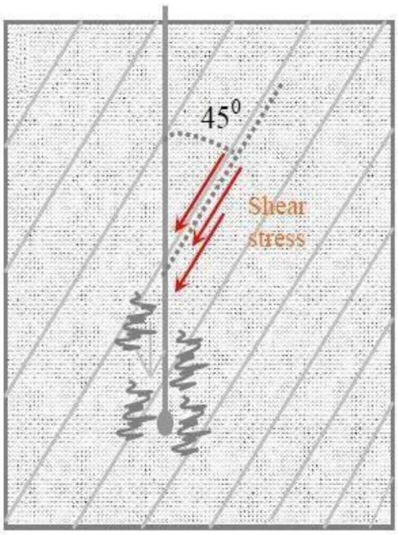


Figure 23: Direction of Shear Stress in the Maximum Failure Probability of Wall Collapse [29]

The maximum shear stress direction will follow the bedding plane. Therefore, shear stress failure could be a potential reason for failure. An induced failure direction will be developed if the borehole is drilled at 45º to the weak planes. Accordingly, drilling a well in such conditions represent the biggest risk for wellbore stability.

Flowing formations, Plastic shales

Plastic shales can potentially cause stuck failures in boreholes. In the case that drilling fluid has low viscosity, some shales can behave plastically flowing in the borehole and produce pipe sticking. Using a low mud density, mud is not capable to compensate the pressure produced by the flowing shale and in that case, a sticking failure can happen. This is mostly connected with salts and plastic shales. Plastic shales are frequently sticky and have a big amount of swelling minerals (montmorillonite, smectite), therefore, plastic shales are closely connected with swelling shales failures.

2.4.2.2 Mechanical Sticking

Mechanical sticking refers to several cases and the most vital are the cuttings accumulations because of pore hole cleaning and key seating due to a deviation in the hole.

Hole Pack Off

If the cuttings are not properly removed from the well, they will eventually accumulate in the well, causing drill string to pack off (Figure 24). Poor hole cleaning will result in an accumulation of cuttings in the annulus with potential sticking the drill string. This issue is frequently encountered in washouts or cavities spots where annular velocities of fluids are reduced.

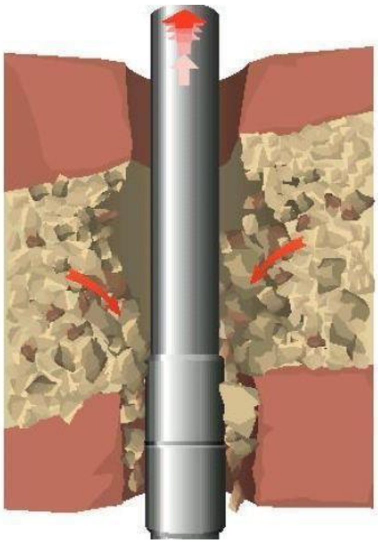


Figure 24: Hole Pack off Caused by a Formation Washout [26]

A normal field practice is to first circulate bottom several times with a drill bit off bottom to circulate out any cuttings bed that could be present before making a trip. Torque/drag increase and sometimes circulating drill pipe pressure are indications of great accumulations of cuttings in the annular space.

Hole pack off can be produced for several reasons:

- Drilling at extreme ROP
- Inadequate mud properties to carry out cuttings
- Highly deviated wells
- Few cuttings returning at the shakers
- Formation washouts

Key Seating

Key seating is often mechanical failure produced in boreholes where there is a big deviation of the strings (Figure 8). Mostly, this failure is often connected with doglegs or washouts in the boreholes. Soft or medium-hard formations have a big tendency to create key seating. The dipping angle of the formation is playing a big part in the hole deviation as well. The optimal orientation should be crossing the formations perpendicular, the closer the dipping angle of the materials is to the axis of the well, it is going to be easier to deviate the well.

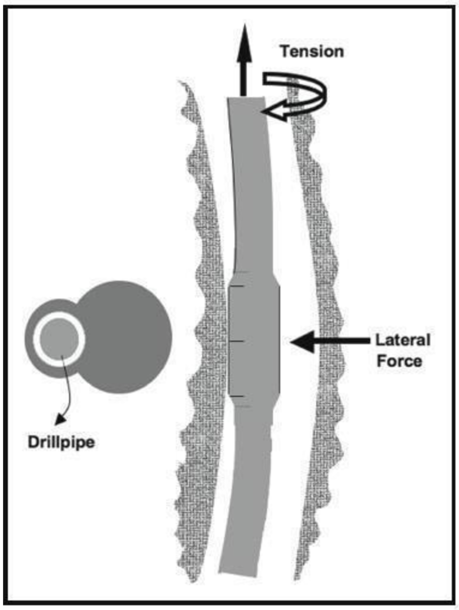


Figure 25: Pipe Sticking Caused by Key Seating [25]

Identification signs for Key Seating are:

- Circulation is not restricted
- Tripping back is possible
- This situation happens when pulling out of a hole
- High over pull is suddenly seen when the BHA is pulled into the key seat

2.4.3 Methods to Prevent Stuck Pipe

2.4.3.1 Data from Offset Well

Before the well is planned, all personnel included in the process of planning should first collect data from offset wells. An offset well is a well drilled in the area of other wells. They offer plenty of information that can be used for correlation with the current planning of the new well. [30] For that resolution, the following should be well-known:

- Record of key seating along with associated dog leg severity and ROP through the well section.
- The depth and thickness of the permeable, unconsolidated formations and salt zones should be noted along with the drilling fluid properties used.
- Record of any hole cleaning problems.
- Formations that caused circulation problems and the mud weight used.

2.4.3.2 Planning

When the well is planned in addition to the data provided by offset wells, thefollowing should also be applied:

- o Identification of the potential troublesome zones and any special procedures adopted through these formations.
- o A top drive is well recommended for known sticking zones since top drives have proven themselves as very efficacious tools in reducing tight hole problems.
- o Keeping BHA length short and the OD of the BHA collars to a minimum. [30]

2.4.3.3 Rig Operating Guidelines

These are some useful practices that can avoid stuck pipe:

- o Keep the drill string moving as much as possible in an open hole.
- o Forcing the drill string through a tight spot may lead to the drill string becoming stuck.
- o Wiper trips should be made regularly according to predetermined procedures as the hole conditions command [30].

2.4.3.4 RSS (Rotary Steerable System) Technology

RSS or rotary steerable system is an evolution in directional drilling compared to steerable motors such as PDM. It has two steering concepts: push the bit and point the bit. Push the bit system bends the drill bit by applying the side force to the bit, i.e. pushing it against the borehole to achieve the desired direction. Point the bit deflects the bit off-center to the tool, i.e. pointing the bit to the desired direction. Point the bit works on the same principle as the one present in bent housing motorsystems.

RSS allows continuous rotation of the drillstring, therefore, guides well trajectory without sliding. It is its key benefit which leads to higher ROP, better hole cleaning, reduce torque and drag, progress hole quality, reduce trip time, reduce tortuosity, etc. The reason why continuous rotation of drillstring is so beneficial, is that without proper rotation, the entire drillstring would lay on the bottom side of the borehole wall, making it difficult to achieve anticipated WOB which leads to minimization of planned ROP. Rotation of the drillstring which RSS delivers minimizes the risk of pipe stuck and buckling. Sliding creates more problems since the lack of rotation keeps the drilling mud in the static state, resulting in cutting removal not to be efficient as desired. Because of it cutting then pack off around the BHA, causing the drillstring to stick, i.e. causing drag to increase. The only drawback of RSS over mud motors is that RSS costs more on daily basis but this could be easily acceptable if a certain well would be drilled much faster resulting in less money spent at the end of the day [19, 20, 31].

2.4.3.5 Spiral DrillCollars

The spiral drill collars are a common type of collars used in are which is prone to differential sticking. The spiral cut on the collar wall will help move cuttings in a tight hole. This cut will also reduce the surface area and allow mud and cuttings to pass around the drill collar. [32]

2.5 Summary

After reviewing the most vital drilling problems during constructing wellbore W-1 JR, table 1 shows the most suitable solutions which will be in the following chapters evaluated in order to maximize and enhance drilling efficiency.

Table 1: Summary of Drilling Problems and Solutions

Drilling Problems	Preferred Solutions
Bit Balling	Modification in Bit
	Drilling Hydraulics Modification
	WBM with additives
	OBM
	Electro-Osmosis Coating
High Torque and Drag	Lubricants
	Co-Polymer Beads
	Increasing Rig Capabilities
	Pressure Pulse Reduction Sub
	Mechanical Friction Reduction Sub
	RSS
Stuck Pipe	Spiral Drill Collars
	RSS

Chapter 3 Risk Management and Evaluation Methods

3.1 Risk Estimation

Risk is an indispensable part of every organization, whether an institution, an enterprise, a unit or an enterprise, faces risk. Most organizations consider the risk a negative phenomenon, so they view it as an expected loss resulting from the likelihood of a loss occurring and the value of the loss. The problem with this definition is that risk is viewed as something negative, or as a potential loss. However, management is increasingly seeking to monitor risk through:

- Range that covers risks and chances,
- Gains and losses that include both positive and negative results,
- Probability of occurrence and consequence [49].

Risk represents uncertainty about the outcome of expected events in the future, that is, a situation where we are not sure what will happen and reflects the likelihood of possible outcomes around some expected value. In doing so, the expected value is the average result of repeated contingencies [50].

The results of the manager's assessment depend on whether the assessment is made in safe conditions or when there is risk or uncertainty. Related factors that make the decision-making framework are the type of problem, decision making, and the solution to the problem. Confidence in the correctness of the decision is very high when made in security conditions, lower in risk circumstances and lowest in uncertainty. The goal is to make the best alternative decision, whose choice is a complex problem and depends on:

- possible alternatives,
- consequences,
- values,
- facts taken into account in the case
- making a decision,
- used methods [51].

When it comes to risks, businesses have three options. They can try to reduce them by changing their business or performing some specific activities to improve control and flexibility. In addition to reducing the risk, companies may either choose to retain the risks as they are, or at least part of the risk may try to transfer to someone else, for example by purchasing insurance contracts or other financial instruments [52].

Risks are an everyday issue of strategic management, development, study and organizational theories. Risk represents a unit of uncertainty, and given its measurability, risk can also be managed.

Risk management is the process of measuring, assessing and developing strategies to control it. Enterprise risk management refers to events and circumstances that may adversely affect the enterprise (affecting the very survival of the enterprise, human and capital resources, products, and services, consumers, as well as external influences on society, the market and the environment).

Risk management is done in several different ways, such as reducing, avoiding, associating, taking over and moving risk. Participants in the risk management process are the project director, head of the risk department, potential risk bearer and activity bearer. Based on research and study of the state of the enterprise, risk managers make suggestions for eliminating risk factors in order to reduce risk and uncertainty and allow normal conditions for the quality work of the company. A well-organized risk management process must carefully and expertly identify and analyze risk.

Risk management is not about avoiding risk, it is about making decisions that risk is taking, and is an added value to the organization and its participants. Risk management makes several points in its implementation process:

- creates a framework for future activity (consistency and control),
- Improves decision making (planning, prioritization through a comprehensive and structured understanding of business activities, volatility and project opportunities/ threats),
- contributes to a more efficient use/ allocation of resources,
- reduces the volatility of less important business areas,
- preserves and strengthens the assets and image of the organization,
- optimizes implementation activity [53].

Risk management should develop the process by which the enterprise strategy and its implementation are implemented. The risk management process begins with the strategic goals of the organization, continues with risk assessment, risk reporting, decision making about residual risk, and ends with oversight.

Methods and procedures used for risk analysis and assessment are specifically defined in relation to each type of risk. Risk analysis and assessment can be carried out on the basis of qualitative and quantitative methods such as questionnaires, stress tests, and scenario analyses.

In the assessment, it is also necessary to distinguish between gross and net risk assessment. Gross risk assessment refers to the assessment of the situation prior to the application of risk management measures and the net risk assessment takes into account existing risk management measures.

In the first step, the risk assessment must always be qualitative. A quantitative assessment is conducted after some risk has been defined as significant. Qualitative assessment is only used if a quantitative assessment is impossible or economically unreasonable for some types of risk. In that case, the qualitative assessment shall be explained in detail.

The result of risk analysis and assessment are all risks in the company that has been taken into account within the available risk-bearing capacity of the company. The result of analysis and assessment are risky (net) positions that are actively influenced by risk management measures, with the aim of reducing the likelihood of occurrence (e.g. by establishing controls and limiting the amount of damage) or limiting the amount of loss (e.g. risk transfer).

It is necessary to ensure that the management of the company is informed about the current risk profile, or about possible losses from individual risks so that the management of the company can adequately respond by taking management measures and changes [54].

Risk measurement. Successful risk management requires accurate and rapid measurement of risk exposure.

There are several methods of measuring risk, but they all have the same objective, which is to estimate the variation of a measuring magnitude, such as profit and market value of instruments, with the influence of input parameters such as interest rate, exchange rate or other parameters. Some methods, or specific quantitative risk indicators, can most often be grouped into three types:

- Sensitivity - shows changes in the measurement magnitude caused by a unit change in one of the input parameters (e.g. a change in the value of bonds caused by a 1% change in the interest rate)
- Variability - shows the variations around the mean of one of the input parameters or measurement size
- Risk projection - shows the magnitudes with the worst-case scenario for the event occurrence set point.

Different types of risk indicators create a complete picture of the effects of risk because they cover its different dimensions. Risk projections are the most comprehensive risk measurement methods because they integrate sensitivity and variability with the effect of uncertainty.

The VaR method (Value at risk) is a third group of measurement methods and is one of the most commonly used methods. A standard for measuring and controlling market risk, called VARs, is generally defined as the maximum expected loss of a particular financial position or portfolio with a fixed time horizon under normal market circumstances and with a predetermined confidence level.

Risk insurance. Managing transferable business risks means, to the extent possible, to ensure business risks and thus counteract the negative effects, i.e. reduce them to a tolerable minimum. Risk management can be defined as taking actions designed to minimize the negative impact that risk may have on an entity's expected cash flows, that is, deciding what risks an entity should be exposed to, and to what extent, and what risks an entity will provide and by external or internal methods, and applying payment security instruments [55].

Risk control. The risk management system contributes to sustainable success, enabling continuous business success based on the principles of quality and control, sustainable development, social responsibility, and business ethics. The viability and success of the business enable systematic risk management based on standardized and controlled processes. After identifying, analyzing and assessing risks, an important step in considering the transgressions in risk management control and standardization is the choice of techniques to use for each. Risk management has two basic approaches: physical control methods and financial control methods.

Once the defined and selected risk control actions become a part of the risk management process. The actual implementation of actions in the process is a particular issue for organizational management, and the methods alone do not provide detailed support for the way in which this is performed.

In order to standardize approaches to the construction of risk management systems and risk management processes, international standards have been developed. Norms or standards have been adopted in all industries, so there are ISO standards characteristic primarily in the trade of goods and services, the Basel standard in banking and the Solvency standard in the insurance industry [55].

The risk management system protects the company and all its partners and associates by adding value to them by creating a backbone that enables them to carry out activities consistently and in a controlled manner. In addition to improving the decision-making process, it enhances business transparency and planning and prioritization through a comprehensive and structured understanding of the volatility of business activities.

3.2 Evaluation Decision Methods

Decision making is an important factor in every business, that is, it is crucial because it affects the success of the business. Therefore, the company is expected to make reasonable and constructive decisions. Often, different criteria should be taken into account when making decisions. For this reason, tools are used prior to decision making to identify more clearly the key factors that drive the best decision. For the evaluation decision-making process, two methods will be used. Those are the weighted decision matrix method and the probability of success method.

3.2.1 Weighted Matrix Method

Weighted Matrix (WM) is a simple method that can be extremely useful when complex decisions need to be made. This is especially true of situations where there are numerous alternatives and criteria that are of varying importance and all of the above should be analyzed or taken into account.

WM is often used in design as a quantitative method for evaluating alternatives. It is a tool that compares alternatives based on multiple criteria at different levels of importance. It can be used to rank all alternatives with respect to the main reference and thus obtain the order of alternatives in order of importance [56].

Table 2: An Example of Using WM

CONCEPTS										
		REFERENCE TRIP		Trip A		Trip B		Trip C		
Criteria	Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Travel cost	0.25	0	0	1	0.25	0	0	-1	-0.25
Total Cost	0.2	0	0	0	0	1	0.2	-1	-0.2
Novelty	0.15	0	0	2	0.3	1	0.15	2	0.3
Locations	0.1	0	0	-1	-0.1	0	0	2	0.2
Travel time	0.1	0	0	0	0	-1	-0.1	1	0.1
Safety	0.1	0	0	2	0.2	1	0.1	2	0.2
Accommodation	0.05	0	0	-2	-0.1	-1	-0.05	2	0.1
Travel quality	0.05	0	0	-2	-0.1	0	0	2	0.1
TOTAL			0		0.45		0.3		0.55
RANK					2		3		1
CONTINUE?					yes				

WM is done by first making a list of all choices, i.e. possible choices. This is followed by the identification of impact criteria, that is, criteria that affect individual decisions. The following is an evaluation of each criterion and thus gains its importance and influence on the decision. The rating scale should be clear and consistent because this is the only way to obtain a scale of criteria from insignificant to those with the greatest impact. Good implementation of the criterion evaluation helps to calculate the relative importance of each criterion. The following is a calculation of the weighted scores by multiplying each choice score by their importance. The results obtained for each alternative are added together to arrive at a final result for each alternative. The end results are then compared with one another [57].

3.2.2 Probability of Success Method

Probability theory is a mathematical discipline that deals with the study of random phenomena, that is, empirical events whose outcomes are not always strictly defined. One of the basic tools in probability theory is an experiment that examines the link between cause and effect. The outcome of an experiment is often influenced by multiple conditions and if the experiment is repeated several times under the same conditions, some regularity occurs within the set of outcomes. Probability theory deals with such regularities by introducing a quantitative measure in the form of a real positive number, that is, probability. Probability estimates the possibility, that is, the inability to achieve the outcome.

The basic concepts of probability may differ depending on the point of view, and the results and interpretations of the results may differ. The laws of probability are not always simple and easy to understand. Everyday experience and logic used in life are often not in accordance with the laws given by statistics. The term known as "subjective probability", which describes these differences in approach, belongs to psychological rather than statistical terms and therefore often has little in common with mathematical probability. The most common use of probability is when playing the lottery. It is often believed that a major lottery win will be won, and there is virtually no consideration for the likelihood of a car accident, although such a probability is far greater than that for winning the lottery.

The basic term in probability theory is the set Ω which represents the set of all possible outcomes ω of an experiment. The set Ω is called the space of elementary events. A random event is defined as a subset of Ω. Event A ($\subset \Omega$) is realized only and only if an outcome ω belonging to subset A is achieved. The set of all events corresponding to one experiment is called an event field and is denoted by F. The event field always contains Ω ($\in$ F) as possible event and 0 ($\in$ F) as an impossible event. The events below are capitalized (A, B, C…) and are considered to belong to the event field F.

If event A also causes event B, event A can be said to imply event B, which in set theory means $A \subset B$. If $A \subset B$ and $B \subset C$ is true, then $A \subset C$ is implied, and if $A \subset B$ and $B \subset A$ then events are equivalent and it is written A = B. For event A, there is an opposite (complementary) event $\bar{A}$ that occurs if event A does not occur, that is, $\bar{A} = \Omega \setminus A$.

The product of two events A and B is denoted by AB and represents an event that only occurs if both events A and B occur. The product of events A and B is the intersection of sets A and B, respectively, and $A \cap B$. If A and B are disjunctive sets, i.e. $A \cap B = 0$ it is said that events A and B are excluded. The sum of two events A and B is denoted as the union of two sets $A \cup B$. The difference A and B is considered to be an event that occurs if at least one of A or B occurs and we denote the operation by $A \setminus B$ [58].

The probability of success (POS) method is a statistical method that is closely related to the conditional power and predictive power. The probability of success is the ratio of success cases to all outcomes. Perspective estimation is a parameter of the expectation curve indicating the possibility of being more than a minimum. If the minimum volume is zero, the probability of success is called "geological" or the probability of "technical success". If agreed economic minimum value determines what success is, the probability of success after the outage may be significantly lower [59].

The probability of success method is very useful for evaluating the success of individual decisions because it takes into account the risks that arise in a particular process, or are part of a particular decision. Within this method, potential risks are considered. The method analyzes the available information and, based on the results obtained, determines how much a particular decision or other parameter is likely to succeed [60].

3.2.3 Other Evaluation Decision Methods

3.2.3.1 The AUVA Method

The AUVA method is the most commonly used risk assessment method. It is tailored to identify and evaluate the deficiencies and risks that can lead to occupational injuries or diseases. The basic pre-assessment of residual risk assessment is to align the analysis with the requirements of the workplace means and to determine the application of basic occupational safety rules.

The AUVA method identifies various gaps in the application of basic rules on machinery and work equipment, work and auxiliary premises, installations, plants, etc. The analysis of the application of occupational safety measures over work equipment and the application of special occupational safety rules are carried out, in particular the ability of the employees themselves to organize and manage or to work safely in their jobs and tasks.

A further procedure for developing a risk assessment according to the AUVA method is to numerically calculate the risk and determine the residual risk, that is, the risk that exists during the performance of operations and with the change of specific occupational safety rules.

The AUVA method developed a numerical calculation of the risk for [61]:

- Mechanical hazards
- Dangers of falls
- Electric hazards
- Hazards caused by chemical, biological and physical harms

3.2.3.2 The SME Method

The SME method is a numerical method of the European Community for small and medium-sized enterprises based primarily on the avoidance of hazards according to their place of origin. The main measures to counteract unavoidable hazards include the development of technology, the adaptation of the work itself to the individual, the training of employees, the organization of the transfer of authorizations and the activities of employees in occupational safety and health [62].

3.2.3.3 The WKÖmethod

The WKÖ method was developed by the Austrian Chamber of Commerce. It provides a quick and correct assessment for the person who does it, and its table contains five possible conclusions, which greatly shortens the risk assessment itself. Using its risk assessment matrix, it describes:

- Biological substances
- Fire and explosions
- Hot and cold substances
- Radiations and fields
- Microclimate
- Lighting
- Monitoring and handling factors
- Physical endeavors
- Psychic and organizational conditioning efforts.

As can be seen, there are other methods by which risk can be assessed. However, the choice of the method also depends on the type of risk, the area of assessment and other factors to consider when selecting the method. The choice of subject methods, the weighted matrix method and the probability of success method, is a consequence of the specificity of the risk assessment and their impact on the decisions or changes. These methods provide a good insight into the direction of decision-making, i.e. how future activities should be conducted. For this reason, it was decided to use the methods mentioned above.

When it comes to methods for comparing risk assessment, a matrix of predefined values can be extracted. This method of risk assessment uses three parameters: resource value, threats, and vulnerabilities. Each of these parameters is scrutinized for possible consequences, while threats are considered for the respective vulnerabilities. Also, the method is the ranking of threats by risk assessment. This method of risk assessment formally uses only two parameters: the impact on the resource (resource value) and the likelihood of a threat. It is implicitly understood that the impact on the resource is equivalent to the value of the resource, while threats are viewed against the corresponding vulnerabilities. In this way, the estimated risk becomes a function of several parameters.

The assessment of the value of the realization and the possible consequences is also used for comparative risk assessment. The risk assessment process in this method is somewhat more complex than in the previous two and is carried out in two steps. The first is to define the value of a resource based on the potential consequences of a threat. Then, based on vulnerabilities and threats, the probability of realization is determined [63].

3.3 Monte Carlo Simulation

Monte-Carlo methods are stochastic (deterministic) simulation methods, algorithms that predict the behavior of complex mathematical systems using random or quasi-random numbers and large numbers of calculations and repetitions. Monte Carlo simulation is synonymous with simulations that solve probabilistic problems. The values of the random variable for which the simulation is performed are selected from the probability distribution function corresponding to the actual occurrence of the default and are entered into a computer program.

All values of the dependent variable have the same probability resulting from the selected distribution function. Namely, any way to solve a problem that relies on generating a large number of random numbers and observing the proportion of those numbers that exhibit the desired properties is called the Monte Carlo method. The Monte Carlo Method was designed by Stanislaw Ulam in 1946 while working on the development of nuclear weapons at the Los Alamos National Laboratory and was named after the Monte Carlo casinos where Uncle S. Ulama often gambled. The value of the method was soon recognized by John von Neumann, who wrote the program for the first electronic computer, ENIAC, which solved the problems of neutron diffusion in fissile materials by the Monte Carlo method.

The value of the Monte Carlo algorithm lies in the fact that it gives all possible outcomes as a result, but also the probability of occurrence of each of these outcomes. Furthermore, it is possible to perform sensitivity analysis over Monte Carlo simulation results in order to identify the factors that most influence the outcome of the process in order to limitor emphasize their influence, depending on their nature. The algorithm can be explained as follows [64]:

1. Mathematically model the business process.
2. Find variables whose values are not completely certain.
3. Determine density functions that well describe the frequencies at which random variables take their values.
4. If there are correlations among the variables, make a correlation matrix.
5. In each iteration assign a random value to each variable derived from the density function taking into account the correlation matrix.
6. Calculate the output values and save the results.
7. Repeat steps 5 and 6 n times.
8. Analyze the simulation results statistically.

The Monte Carlo method is similar to what-if analysis except that what-if does not take into account the likelihood of an event, while the Monte Carlo method also takes probabilistic into account, making it a more appropriate tool for decision-making under risk conditions.

The Monte Carlo simulation is the most accurate maximum loss estimation method, also known as a statistical simulation method, where statistical simulation is defined as any method that uses sequences of random numbers to perform a simulation.

The Monte Carlo simulation is very similar to the historical method in that the assumptions about future risk based on historical data are used in the calculations. The difference is that hypothetical changes in market factors are not created on the basis of past observed changes, but rather through statistical simulation adequately generating returns similar to those of the past.

Also, after the simulation obtained, the risk value is determined with a certain level of probability as in the historical method. The method allows the use of estimation parameters of theoretical distributions based on historical data, taking into account market expectations, which can become more demanding and precise as needed [65]

3.3.1 Probability Distribution

Probability distributions have been designed to fit special purposes. The probability distribution can be discrete or continuous depending on the nature of the variable. Binormal, Poisson and Multinomial are called discrete distributions while normal, lognormal and triangular are continuous distribution examples.

There are two ways to illustrate the continuous probability distributions. The first one is the probability density function that shows variables of the interested parameter with their frequencies. The second one is cumulative density function and it shows variables of the interested parameter with their probabilities.

The probability of any variable that is presented in the cumulative density function graphic is determined by calculating the area on the left side of the interested variable under the curve in the probability density function graphic.

3.3.1.1 Triangular Distribution

The triangular distribution is a nonstop probability distribution with the minimum value at a, maximum value at b and its peak value at c, sometimes defined as the lower limit, upper limit, and mode respectively. It can be symmetrical or tilted in either direction. It is typically used when there is boundary sample data available, especially in cases where the association between variables is known but data is limited.

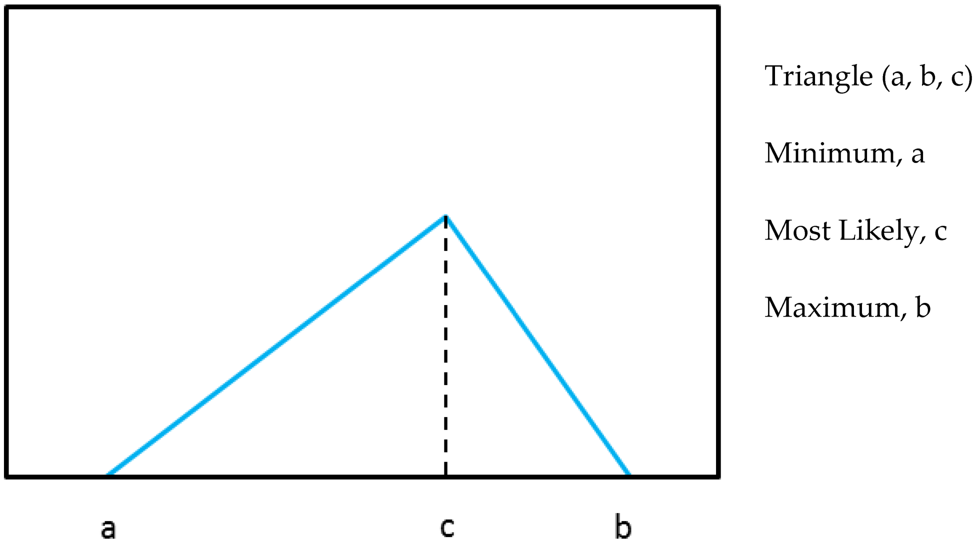


Figure 27: An example of Triangular Distribution

The triangular distribution is used when the historical data are not available and then a better distribution couldn't be figured out. However, the project team had a guess for a minimum, a most probable and a maximum value for a triangular distribution.

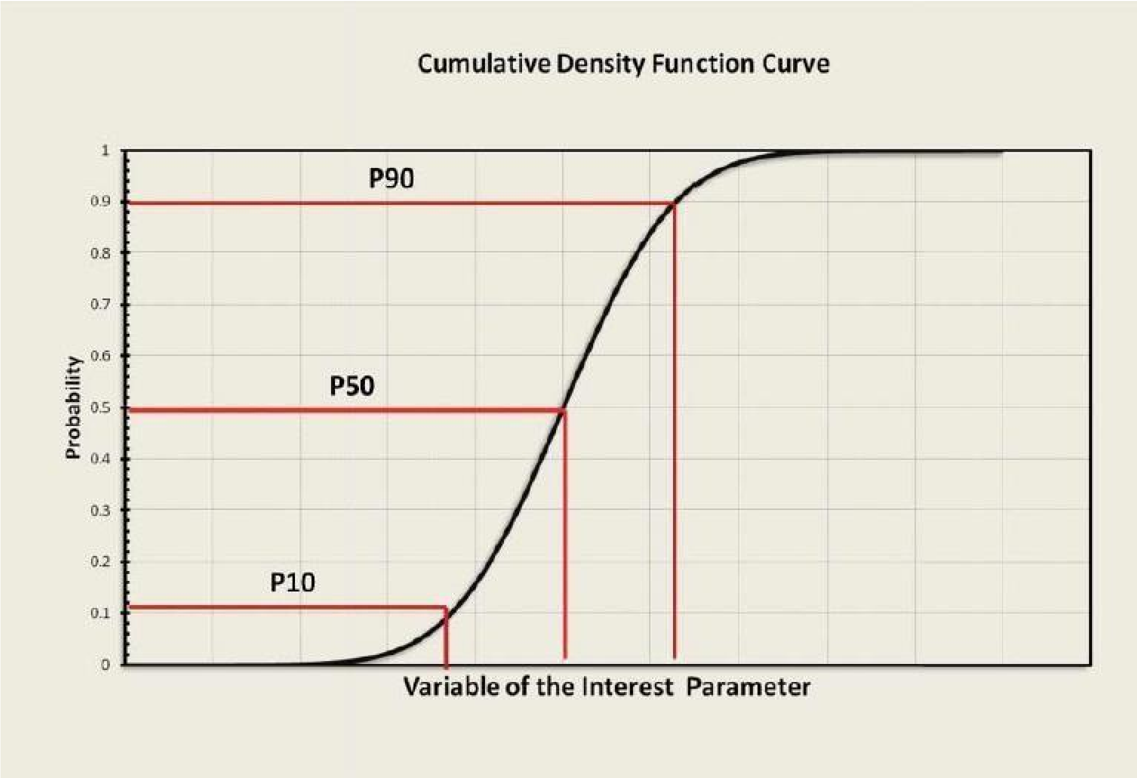


Figure 28: An Example of Cumulative Density Function

P10

It is the probability that is likely to be met 90% of the time. It is widely used in the oil & gas industry and it provides an accurate and reliable estimate.

P50

It the key figure in most probability estimations. As obscure, there is a 50% chance for the interested parameter to be less than this figure and 50% chance to be more.

P90

It has only a 10% chance of being realized. It is a highly optimistic estimate which can be only achieved under exceptional circumstances. It may represent the upper limit of the available technology.

Chapter 4 Methodology

4.1 Overview

In this chapter, the development phase of the evaluation decision-making process will be explained. At this point, a lot of different tools for evaluation and decision-making process are available in the market. The weighted matrix method is one of these tools. This tool consists of establishing a set of criteria options (KPIs) that are then assigned with the weighted factor. The main advantage of this method is that it is very simple and it can be very valuable in making complex decisions, particularly in cases where there are many other possibilities and many criteria of variable importance to be considered. The limitation that this tool brings is that there are a lot of criteria options with uncertainties in the evaluation decision-making process which directly influences the final weighted matrix output. To make the evaluation decision-making process more reliable, another evaluation tool was presented. It is the probability of success method. This method uses two different groups of KPIs to calculate probability distributions of selected targets. Based on probability distributions probability of success will be estimated. Combining these two tools, the weighted matrix method and the probability of success method into an Integrated approach will produce a more reliable output in the evaluation decision-making process.

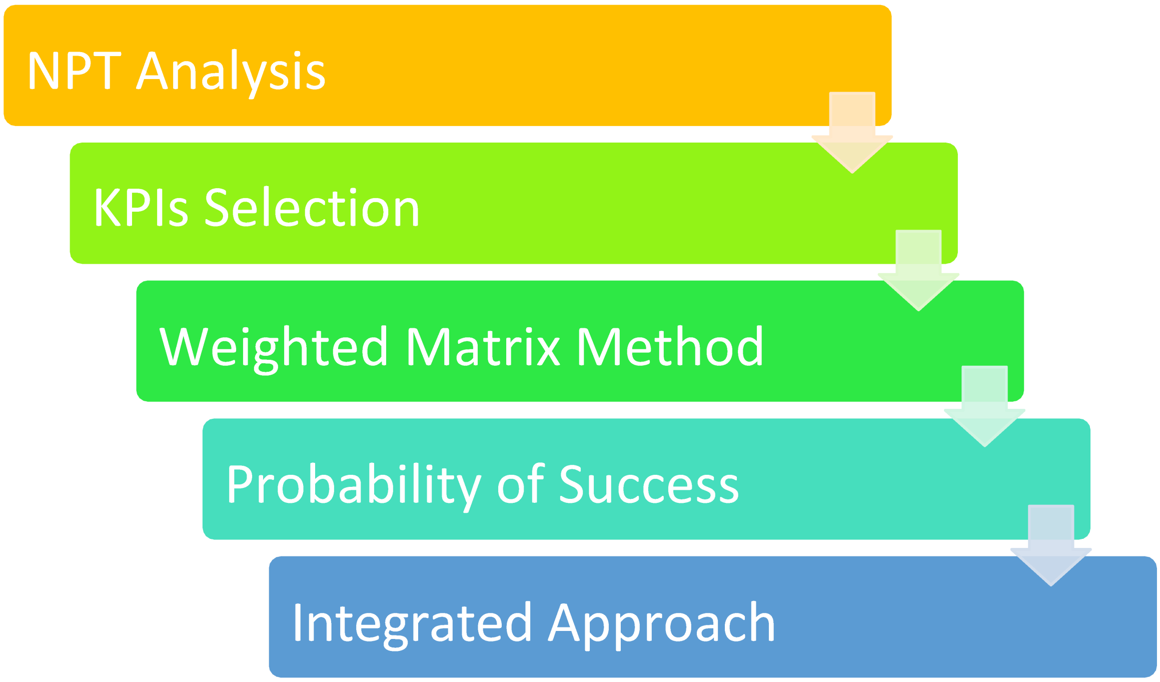


Figure 29: Workflow Main Phases

Figure 30 displays the steps of analysis and methods used in this evaluation decision-making process. The workflow was planned in the way that it covers the procedures and requirements to deliver reliable and reasonable results, which will help to improve the decision-making process. Overall, the workflow consists of five phases. The first step is the Non-Productive Time analysis.

4.2 Non-Productive Time (NPT) Analysis

NPT analysis shows how much time is lost to any event which causes a time delay in the progress of planned drilling operation. NPT analysis will produce major drilling problems. Based on those problems, drilling methods will be proposed and that is the reason why there is a need for it to be the first step in the workflow of the case study evaluation decision-making process.

NPT analysis was performed by looking at the daily morning reports and from there, all the operations were gathered into a table and divided by class codes, major operation codes, operation codes, and trouble type codes (See more detailed classification in Appendix A). Trouble codes define if there is any NPT. After looking at the trouble codes section, NPT operations can be summarized and the major NPT root causes can be seen (Figure 31).

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Task Start Time	Task End Time	Task Duration [hrs]	Start Depth [m]	End Depth [m]	ROP	MD [m]	MW [sg]	Activity Description	Class Code	Major Operation Code	Operation Code	Trouble Type
71	10.5.18. 7:00	11.5.18. 7:00	12,36	1791,00	1888,00	7,85	1795,5	1,18	Drilling horizontal section wit 8 1/2" bit (sliding and rotary) WOB= 10-25 t, Q=1 500 l/min, p= 155-170 bar	PD	DRLG	DMS	BB
72	11.5.18. 7:00	12.5.18. 0:30	6,05	1888,00	1949,00	10,08	1892,5	1,16	Drilling horizontal section wit 8 1/2" bit (sliding and rotary) Bit balling, 22 t Overpull; @1 927 m increase in p (160--> 175	PD	DRLG	DMS	BB
73	12.5.18. 0:30	12.5.18. 1:30	1,00	1949,00	1949,00	0,00	1953,5	1,16	Circulation, p= 192- 200 bar, Q= 700 l/min	TD	DRLG	CIR	MUD
74	12.5.18. 1:30	12.5.18. 5:00	3,50	1949,00	1949,00	0,00	1953,5	1,20	Running tool out (1 949- 1 911 m) with rotation and circulation Q= 630 l/min, p= 175 bar, 30 RPM	TD	CT	TO	LOC
75	12.5.18. 5:00	12.5.18. 7:00	2,00	1949,00	1949,00	0,00	1953,5	1,20	Running tool out without rotation and circulation (1 709- 1 422 m)	TD	CT	TO	NT
76	12.5.18. 7:00	12.5.18. 19:00	2,00	1949,00	1949,00	0,00	1953,5	1,20	Running tool out (1 422 -0 m) 1 422 - 1 058 10 t overpull	TD	CT	TO	DRG
77	12.5.18. 19:00	12.5.18. 19:30	0,50	1949,00	1949,00	0,00	1953,5	1,20	Tool on a surface, PDM failure, bent sub joint unscrewd Drill bit without damage, bit balled	TD	DRLG	HT	TF
78	12.5.18. 19:30	12.5.18. 21:00	1,50	1949,00	1949,00	0,00	1953,5	1,20	Direction drilling tool completion, drill bit exchange Shallow test --> OK	PD	DRLG	HT	NT
79	12.5.18. 21:00	13.5.18. 5:00	8,00	1949,00	1949,00	0,00	1953,5	1,20	Running in directinal drilling tool	PD	DRLG	TI	NT

Figure 30: DDRs Breakdown by Codes

4.3 Key Performance Indicator (KPI) Selection

KPIs stand for key performance indicators and these are the measures of performance, each being made to fit a special task performed. By generating and collecting supreme amounts of KPIs, it becomes easy to statistically evaluate the performance of drilling operations. KPIs were set on personal opinion and by that they can be changed. KPIs will be used as evaluation criteria in the weighted decision matrix and probability of success method. KPIs were set on a lot of assumptions and that is the reason why those methods have a lot of uncertainties. In order to reduce those uncertainties to the minimum, a P50 probability estimation will be performed. In the following section, the inbound KPIs are developed to be used for a case study purpose and they are divided into two groups. The first group is weighted matrix KPIs and the second is the probability of success KPIs. Firstly, all weighted matrix KPIs will be explained and then the probability of success KPIs will be explained.

4.3.1 Additional Incurred Cost

This is the first KPI set in the evaluation process and refers to the extra expenditure needed to implement a selected drilling method. These KPIs have different parameters with uncertainties and in order to reduce those uncertainties to the minimum, P50 estimation will be implemented (Table 3).

Table 3: Additional Incurred Cost

Methods	Parameters						Cost
Modification in Bit	Min Number of Bits	Mean Number of Bits	Max Number of Bits	Min Bit Cost ($)	Mean Bit Cost ($)	Max Bit Cost ($)	P50 Estimated Cost ($)
	2	2.5	3	40,000	45,000	60,000	120,029

4.3.2 Improved Rate of Penetration (ROP)

Rate of penetration (ROP) is one of the most significant factors that affect the economic accomplishment of a drilling operation. ROP is defined as the proportion of the total length drilled to the progression in unit time.

There are two kinds of ROP which can be measured, instantaneous ROP and average ROP. Instantaneous ROP is measured over a fixed time or distance. Whereas, the average ROP is measured over the total interval drilled. There are several factors that have a direct impact on ROP, such as weight on bit, rotation speed, flow rate, bit diameter, bit tooth wear, bit hydraulics, formation strength, and the formation abrasiveness. In directional drilling, average ROP can be used as KPI comparing the efficiency of different drilling methods.

To calculate KPI for different drilling methods, each method was rated with minimum, mean and maximum ROP increase, based on information provided from a scientific paper, and P50 ROP increase value was estimated using Monte Carlo simulation (Table 4).

Table 4: Improved Rate of Penetration Estimation

Drilling Methods	Min ROP Increase (%)	Mean ROP Increase (%)	Max ROP Increase (%)	P50 ROP Increase (ft/h)
Modification in Bit	15	20	40	4.02
Drilling Hydraulics Modification	5	10	20	1.88
WBM with Additives	5	15	20	2.27
OBM	20	30	50	5.42
Electro-Osmosis Coating	40	70	150	8.73

4.3.3 Operational Adjustment Time

Since it is a well know that drilling operations are extremely expensive on a daily basis, it is very important that drilling methods take less time to be implemented. Some methods could take more time than the others and this is measured in KPIs (Table 5).

Each drilling method was assigned with a minimum, mean and maximum time needed to implement those methods. Those values were assigned based on INA engineers' experience and opinion. P50 values were estimated using the Monte Carlo simulation.

After serious consideration of using this KPI in the evaluation process, it was decided that this KPI has arguably reliable data and due to that, this KPI will not enter the evaluation process.

Table 5: Operational Adjustment Time Estimation

Drilling Methods	Min Time (h)	Mean Time (h)	Max Time (h)	P50 Time (h)
Modification in Bit	1	4	8	4.25
Drilling Hydraulics Modification	2	6	24.0	10.12
WBM with Additives	4	6	24.0	10.42
OBM	6	16	36.0	18.78
Electro-Osmosis Coating	1	4	8.0	4.25

4.3.4 Impact

Impact actually indicates a level of performance that labels using the least amount of input to accomplish the highest amount of input. It is a measurable concept that can be determined using the ratio of useful output to the total input. KPIs are based on empirical experience from the oil & gas industry people. Methods are ranked from "1" to "20"; and methods with a higher ranking will have a higher impact. (Table 6.) This KPI refers to the estimating possible improvements in the overall process. It is a concept that measures the ratio of useful output to the total input. Each drilling method was rated with a minimum, mean and maximum possible impact that could bring in improving the drilling process.

It was rated based on INA engineer's opinion and by using Monte Carlo simulation P50 value was estimated and then multiplied with number "20" in order to have these scale in values from 1-20.

After serious consideration of using this KPI in the evaluation process, it was decided that this KPI has arguably reliable data and due to that, this KPI will not enter the evaluation process.

Table 6: Impact Estimation

Methods	Min (%)	Mean (%)	Max (%)	P50 Rating 1-20
Modification in Bit	50	70	90.0	14.01
Drilling Hydraulics Modification	20	40	80.0	9.6
WBM with Additives	50	90	10.,0	16.32
OBM	85	95	100.0	18.75
Electro-Osmosis Coating	60	70	90.0	15.6

4.3.5 Operational Simplicity

Operational simplicity means keeping the drilling process or procedures as simple as possible. Every method will have different procedures to be implemented. The rating was set based on INA's engineer's opinion.

Methods that will require less care to be implemented will be graded with a higher number, while more complicated methods will be graded with a lower number. The ranking will be based on a scale from "1" to "20" (Table 7).

Table 7: Operational Simplicity Estimation

Methods	Rating 1-20
Modification in Bit	17
Drilling Hydraulics Modification	19
WBM with additives	14
OBM	4
Electro-Osmosis coating	16

4.3.6 Improved WellboreStability

Maintaining a stable wellbore is of primary importance during drilling and production of oil and gas wells. The shape and direction of the hole must be controlled during drilling, and hole collapse and solid particle influx must be prevented during production. Wellbore stability requires a proper balance between the uncontrollable factors of earth stresses, rock strength, and pore pressure, and the controllable factors of wellbore fluid pressure and mud chemical composition.

This KPI refers to the possible wellbore stability improvement. Each drilling method was rated with numbers on a scale from "1-20". Higher numbers refer to the drilling methods that will possibly bring a higher positive effect, while lower numbers refer to the drilling methods than will bring less, or they will not bring any effect to the wellbore stability improvement. The assigned numbers were chosen based on information from a scientific paper and in consultation with INA's engineers' team. (Table 8).

After serious consideration of using this KPI in the evaluation process, it was decided that this KPI has arguably reliable data and due to that, this KPI will not enter the evaluation process.

Table 8: Improved Wellbore Stability Estimation

Methods	Rating 1-20
Modification in Bit	10
Drilling Hydraulics Modification	14
WBM with additives	17
OBM	19
Electro-Osmosis coating	11

In the following lines all KPIs related to the probability of success method will be explained.

4.3.7 Additional Incurred Cost

These KPIs are the same for the weighted matrix method and for the probability of success method.

4.3.8 NPT Reduction Savings

This KPI refers to the possible NPT reduction. There are three main drilling problems and each problem has its own NPT. When NPT is related to the drilling methods, the next step is to multiply the number of hours of NPT with the hourly rig rate in order to have this KPI as a cost unit.

4.3.9 Improved Rate of Penetration Savings

This KPI is related to the ROP enhancement. If the average ROP is going to be increased, the total drilling distance will be drilled in a short period of time. This KPI calculates the saved time in a case if the distance will be drilled faster, and then that saved time is multiplied with the hourly rig rate to get this KPI as a cost unit.

4.4 Weighted Matrix Method

4.4.1 Matrix Creation

In this part, different KPIs are established and the corresponding scales are considered for the selection of the optimum drilling methods. KPI is defined as one of the parameters considered in the evaluation of the methods. Each KPI has an attribute scale used to score methods on how well it meets the objective for this attribute. In order to evaluate available methods against each KPI, KPI scales that explicitly reflect the impact on the system selection process are needed. The KPI used in matrix weighted method are listed below:

1. Additional Incurred Cost
2. Improved Rate of Penetration
3. Operational Simplicity
4. Improved Wellbore Stability

4.4.2 Assign Scores to the Methods Using the KPI Scales

For the extra cost and time consuming to implement KPIs, minimum values are defined and for the rest of the KPIs, the maximum values are defined.

4.4.3 Assign Weighted Factor to the Criteria

The final result is moving forward, but still, some work needs to be done. At this point, all criteria are equally important. If the number one thing which needs to be considered as cost due to budgetary decision, then the scores in that column deserve more weight than the others. That means it is time to give weights to all criteria to get a handle on which method scores best in the factors that matter the most to the final decision. In general, weight factors are selected from a decision-maker. For this case study, the base-case weight factors were assigned by the author's personal opinion and by that it can be changed.

A scoring system is going to be used here, using a number from "1" to "5". Ranking a factor as a "1" means it's pretty unimportant in regards to the final decision, while a "5" means it's highly important. By the way, it's effortlessly fine to have two pieces of criteria with the same score (Figure 30).

4.4.4 Weighted Score Calculation

This part involves simple math's operation. For the extra cost and time consuming to implement KPIs, which are defined as a minimum value, the calculation is performed as it follows:

$$\left(\frac{Minimum\ KPI\ Value}{KPI}\right) * KPI\ weightining\ factor$$

For the rest of the KPIs calculation is performed as it follows:

$$\left(\frac{KPI}{Maximum\ KPI\ Value}\right) * KPI\ weightining\ factor$$

4.4.5 Add the Weighted Scores

The complete search optimization model for the system selection problem with four KPIs and the weighted factors are used to find the best-case drilling technology for the re-entry campaign. It is noted that KPIs scores are not evaluated for the empty cells because those KPIs scores are not relevant to the particular subgroups, or because these are already included in technologies within other subjects.

After the optimization system has given the best method, another decision method should be involved in the overall decision-making process.

4.5 Probability of Success Method

The probability of success method is an evaluation tool based on the probabilistic model, assessing the conditional relationship between two target groups. Each target group is defined with several KPIs and each also has its own probability. Cumulative density is a simple multiplication of selected group probability values, defined as discrete values in range 0-1. Reverse density, as its name says, is a multiplication of selected group probability values, defined as values in range 1-0. In the final step, reverse density and cumulative density are being plotted into one graph. The intersection point of the two densities implies the possible savings cost.

4.5.1 Input Data

In this part, different KPIs are established and divided into two groups. The first group consists of negative indicators (NKPI) which include:

1. Additional Incurred Cost

These KPI represent those that could cause extra cost and their summation will express expenditure potential.

On the other hand, there are positive indicators (PKPI) and those include:

1. NPT Reduction Savings
2. Improved Rate of Penetration Savings

These KPIs represent those that could potentially save some money and their summation will express savings potential.

Now, the target groups for estimations are set and the next step is to calculate the probability distribution of two targets, expenditure potential, and savings potential.

4.5.2 Data Extraction for Probability Distribution

In order to extract the data for the two target groups, ModelRisk software for probability distribution was used. More information about the used software is located in Appendix B.

Table 9: Cumulative Density for Expenditure Potential and Savings Potential

Percentiles	Expenditure Potential ($)	Savings Potential ($)
0.01	29,160	59,419
0.03	34,501	64,006
0.05	38,013	68,077
0.08	40,935	71,281
0.10	42,759	72,455
0.15	46,926	75,359
0.20	50,522	77,578
0.25	54,546	79,699
0.30	57,256	81,863
0.35	60,638	83,990
0.40	64,023	85,564
0.45	67,983	87,111
0.50	72,053	88,806
0.55	75,549	90,704
0.60	78,889	92,648
0.65	83,433	94,036
0.70	87,677	96,082
0.75	92,285	98,003
0.80	98,690	99,636
0.85	105,698	102,088
0.90	115,922	105,028
0.92	120,036	106,772
0.95	126,803	109,668
0.97	135,528	112,894
0.99	148,020	118,570

As can be seen from Table 9, Expenditure Potential and Savings Potential are shown as a cumulative density. Expenditure potential stays in original form as a cumulative density, while Savings Potential needs to be changed into reverse density (Table 10).

Table 10: Cumulative Density for Expenditure Potential and Reverse Density for Savings Potential

Percentiles	Expenditure Potential ($)	Percentiles	Savings Potential ($)
0.01	29,160	**0.99**	59,419
0.03	34,501	**0.97**	64,006
0.05	38,013	**0.95**	68,077
0.08	40,935	**0.92**	71,281
0.10	42,759	**0.90**	72,455
0.15	46,926	**0.85**	75,359
0.20	50,522	**0.80**	77,578
0.25	54,546	**0.75**	79,699
0.30	57,256	**0.70**	81,863
0.35	60,638	**0.65**	83,990
0.40	64,023	**0.60**	85,564
0.45	67,983	**0.55**	87,111
0.50	72,053	**0.50**	88,806
0.55	75,549	**0.45**	90,704
0.60	78,889	**0.40**	92,648
0.65	83,433	**0.35**	94,036
0.70	87,677	**0.30**	96,082
0.75	92,285	**0.25**	98,003
0.80	98,690	**0.20**	99,636
0.85	105,698	**0.15**	102,088
0.90	115,922	**0.10**	105,028
0.92	120,036	**0.08**	106,772
0.95	126,803	**0.05**	109,668
0.97	135,528	**0.03**	112,894
0.99	148,020	**0.01**	118,570

4.5.3 Representing Data

This is the final stage in the probability of success evaluation method. At this point, Expenditure Potential and Savings Potential are plotted into one graph (Figure 33). This figure shows expenditure potential (blue line) which starting point is at 0% and end with 100%, meaning the cumulative density grows with cost growth, and the saving potential (orange line) has reverse cumulative density, it starts with 100% and ends at 0%, meaning the cumulative density falls with cost growth.

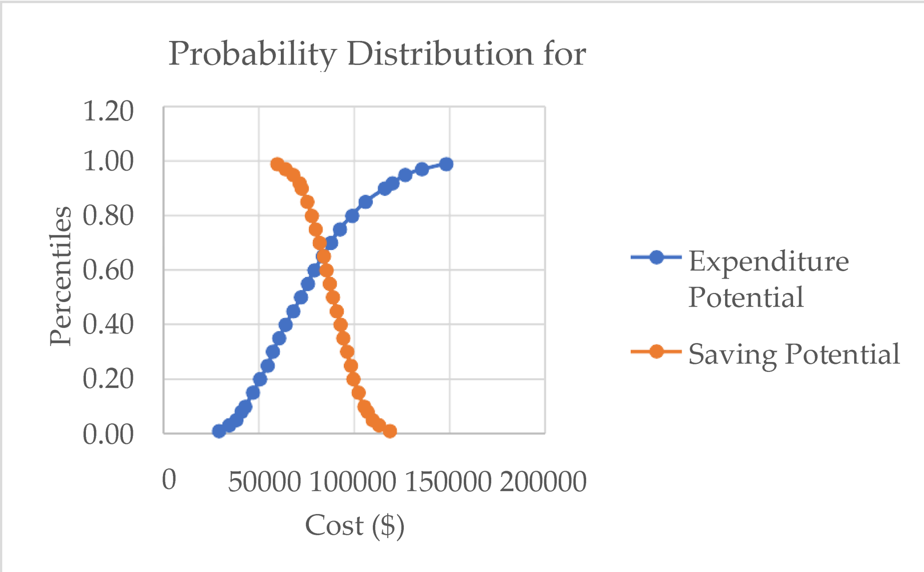


Figure 31: Probability Distribution

The expenditure and savings potential lines meet at the intersection point. This point represents the probability that the required cost for this solution will equal the savings cost and, in this case, equals 0,65 (65 %).

4.6 Integrated Approach

This is the last step in the evaluation decision-making process of the best drilling methods. The integrated approach collects results from the weighted matrix method and probability of success into one table (Table 11). Based on the collected information, a cartesian coordinate system is built in a way that on the X-axis the weighted matrix result is placed, and on the Y-axis are placed the probability of success results (Figure 34). The aim of this method is to choose the method with the best results in both ways.

Table 11: Integrated Approach

Methods	Weighted Matrix Score	Probability of Success
Lubricants	17,0	0,65
Co-Polymer Beads	13,0	0,5
Mechanical Friction Reduction Sub	12,8	0,5
Pressure Pulse Reduction Sub	12,0	0,75
Increasing Rig Capabilities	10,0	0
RSS	18,0	0,96

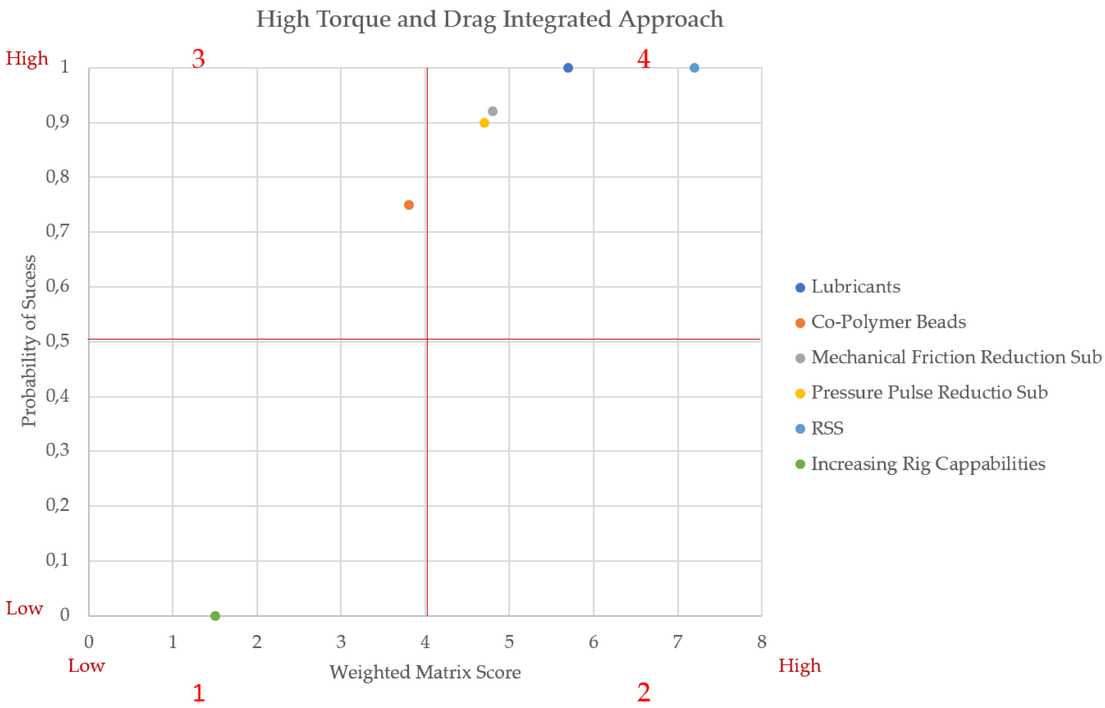


Figure 32: Integrated Approach

To use the integrated approach as an evaluation tool, both the weighted matrix score and the probability of success were divided into low and high values, with 4 and 0.5 being the borderline for weighted matrix score and probability of success, respectively. This means all of the values under 4 and 0.5 are considered low value, and values above that are considered high value (Figure 31). Section 1 is considered to be the most undesirable option, while section 4 is considered to be the most desirable.

The negative aspects of the integrated approach would be that the evaluation decision-making process is built on a lot of assumptions and speculations. There is a lot of space reserved to deal with those uncertainties.

Finally, the biggest advantage of the integrated approach is that it provides the user with a better picture of used drilling methods. For instance, some drilling methods can have very good results in the weighted matrix method, but poor results in the probability of success method. That leads to the conclusion that aa drilling method is undesirable. To have a really good final decision about a chosen drilling method, an integrated approach needs to have good results in both of the evaluation methods. The final estimation is much better and more reliable based on the given information.

Chapter 5 Case Study

5.1 Introduction

Hydrocarbon F-1 field located in Croatia has around 30 wells drilled in the 1990s. Most of these wells are depleted, and therefore the company is planning to launch a re-entry campaign in order to investigate the hydrocarbon saturation in nearby sandstone layers B3 and B5. The main goal of the re-entry campaign is to extract hydrocarbons (oil and gas) from these two different layers. So far one re-entry operation has been successfully completed using conventional drilling technology.

Re-entry well W-1 JR was completed using the old well W-1 JUG. W-1 JUG drilled at the beginning of 1990. While drilling W-1 JR, several challenges were faced by the company such as:

- High Torque and Drag
- Bit Balling
- Stuck Pipe

Consequently, NPT (Non-Productive Time) was 10 days in total and the overall cost was significantly higher than expected. Due to that, the company decided to suspend the re-entry campaign. Reducing drilling time through efficiency advances is an actual method for achieving well cost savings in a standard rig operating rate scenario. A marvelous amount of time in the industry has been devoted to enhancing penetration rates with slight attention to flat time operations that book-end any on-bottom drilling time. As on-bottom drilling time is compact through technological advances and enhanced drilling practices, the total percentage of flat time operations turn into a larger component of the overall time to drill a well. Improving flat time operations should be as high of a priority as on-bottom drilling.

As current oil prices are at a higher level now, it was decided to drill more re-entry wells using different drilling methods in the near future. As it is seen from the list, most of these events have either a direct or indirect relation with the conventional drilling method. Therefore, finding alternative drilling methods may overcome these issues and help saving time and money.

Well Information:

- Well type: Exploration well, Sidetrack
- Elevation: h= 131 m
- Final depth: TVD= 2120 m, MD= 2360 m

- Well trajectory: Directional drilling
- KOP: 700 m
- Turning elements: A= 228,8°, L= 766 m, Inclination angle= 37,9°

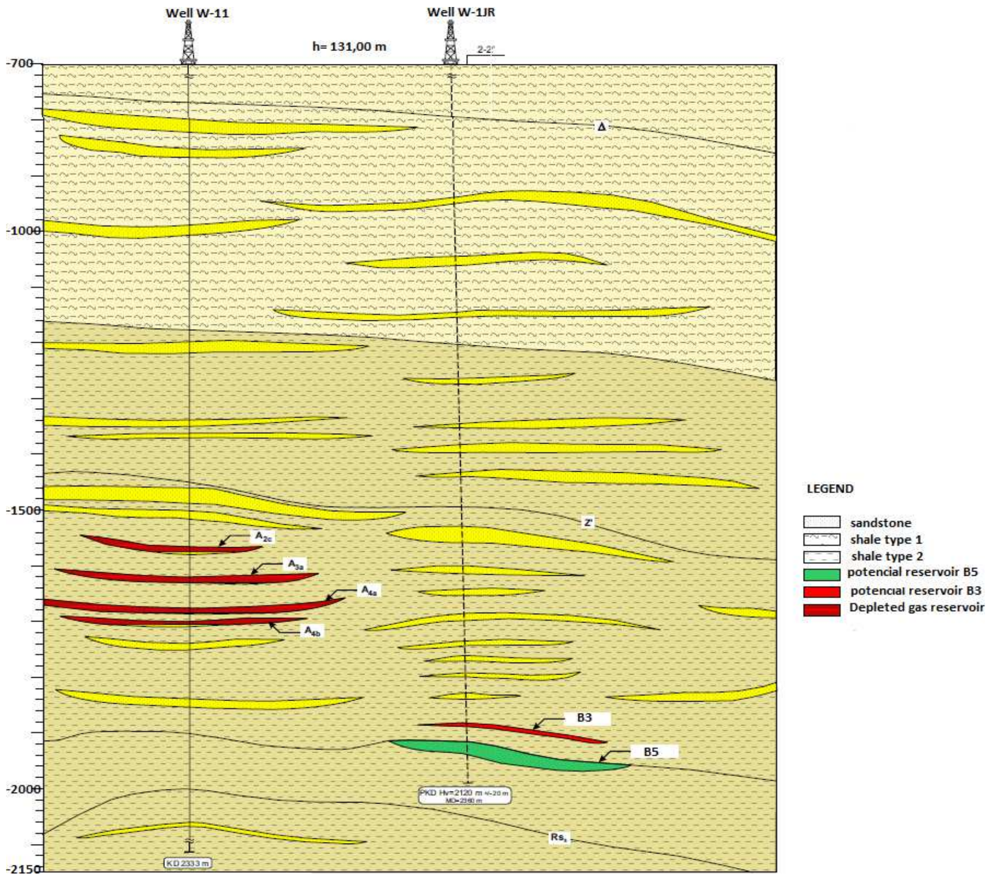


Figure 33: Well Profile

Figure 35 represents well profile and area of interest, potential reservoirs B3 and B5.

Table 12: Well Construction W-1 (Existing Well)

Casing Type	Nominal Outside Diameter mm (in)	Grade	Depth (m)	Nominal Weight kg/m (lb./ft)	TOC
Conductor	508,0 (20")	J-55	0 - 197	137,2 (94)	0
Surface Casing	339,7 (13 ⅜)	N-80	0 - 2093	99,2 (68)	0
Production Casing	244,5 (9 ⅝)	N-80	0 -3515	68,6 (47)	1500

Table 12 shows already existing well W-1 casing design and Table 13 shows planned casing design for new re-entry well W-1JR.

Table 13: Well Construction W-1JR (Planned)

Casing Type	Nominal Outside Diameter mm (in)	Grade	Depth (m)	Nominal Weight kg/m (lb./ft)	TOC
Conductor	339,7 (13 ⅜)	N-80	700 (window)	99,2 (68)	0
Surface Casing	244,5 (9 ⅝)	N-80	700 (window)	68,6 (47)	-
Production Casing	139,7 (5 ½)	N-80	0 – 2360	24,8 (17)	0

The window opening was performed through 2 casing sizes, 9 ⅝ "and 13 3/8"at 700,00 m TVD and it was drilled up to 2360,00 m MD (2120,00 m TVD). A milling job and a whisptock orientation were performed by the Weatherford crew using QuickCut Casing Exit System and Gyro as an orientation tool.

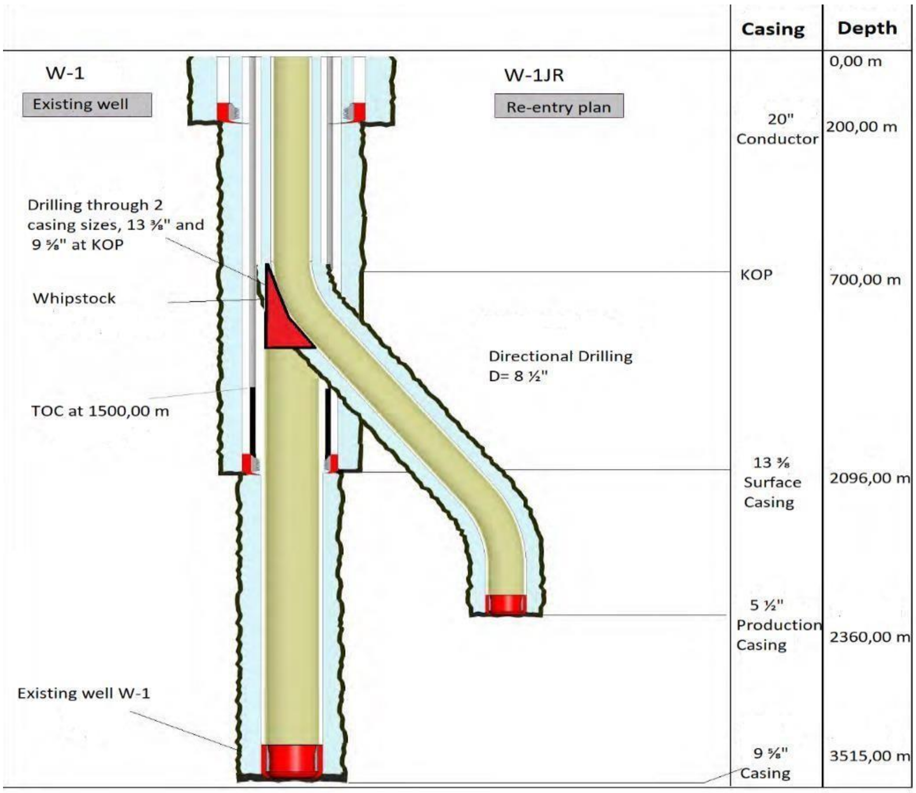


Figure 34: Well Construction W-1JR

Figure 36 represents the final W-1JR well scheme with casing design.

5.2 NPT Analysis

The first step in the NTP analysis was checking DDRs (daily drilling reports) and breaking the data down into codes. The NPT can then be secluded from the trouble code.

After checking DDRs, the final results are given in a table shown below (Table 14).

Table 14: Total NPT by Different Drilling Operations

Description	Trouble Code	Duration (h)	Percentage
Bit Balling	BB	62	25%
Torque and Drag	DRG	88	36%
Loss of Circulation	LOC	3,5	1%
Mud	MUD	8,5	3%

Rig Repair	RR	11,5	5%
Survey	S	3,5	1%
Stuck	STK	54	22%
Tool Failure	TF	12	5%
Tight Hole	TH	2	1%

Taking a look into table 14, it can be seen that NPT takes up 245,0 h in total 721,5 h of drilling. In other words, NPT is equal to 34% of the total drilling time.

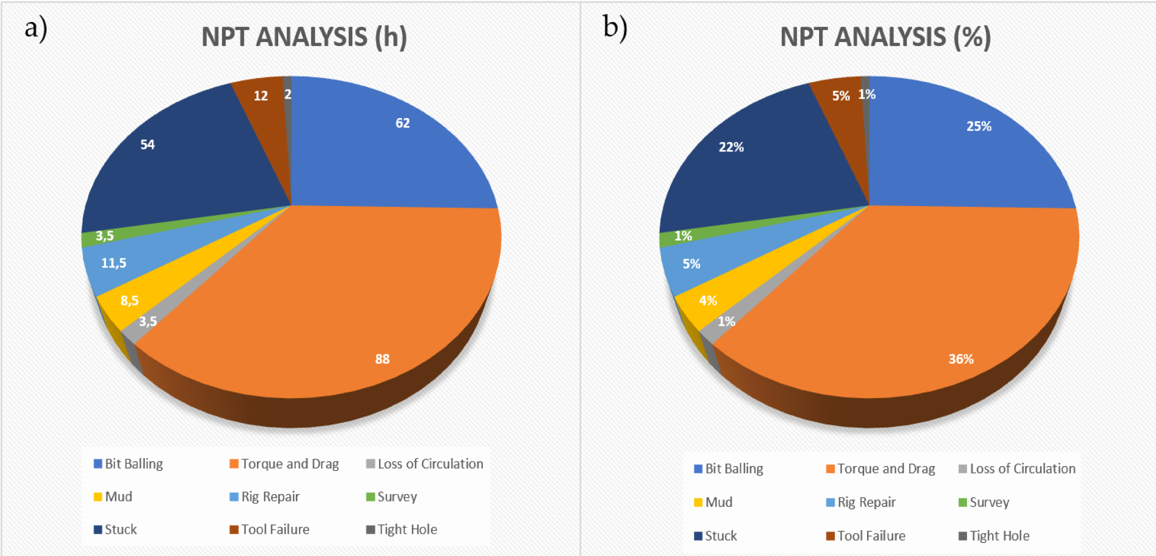


Figure 35: a) NTP distribution in hours; b) NTP distribution in percentage.

The final results, shown on both charts in hours and percentage, clearly indicate the main problems that come with drilling. The first, and biggest problem is torque and drag, taking up 88 h and 36 % of total NPT. The next problem is bit balling, taking up 62 h and 25% of total NPT. And lastly, stuck pipe, which takes up 54 h and 22 % of total NPT.

The NPT analysis is done and the next step is to establish KPIs for the evaluation decision-making process.

5.3 KPI

All KPIs used in the evaluation decision-making process are not reliable and due to that the final output can be taken or considered as effective. A detailed explanation about KPIs selection will be given in the following text.

5.3.1 Additional Incurred Cost

In the table below, all extra cost KPIs are listed. The first column lists drilling methods and other columns, except for the last one, name parameters that are affecting the final price. The parameters were estimated based on a P50 probabilistic concept. A detailed explanation is listed below in Table 15.

Table 15: Additional Incurred Cost Estimation

Methods	Parameters						Cost
Modification in Bit	Min Number of Bits	Mean Number of Bits	Max Number of Bits	Min Bit Cost ($)	Mean Bit Cost ($)	Max Bit Cost ($)	P50 Estimated Cost ($)
	2	2,5	3	40,000	45,000	60,000	120,029
Drilling Hydraulics	Min Cost ($)	Mean Cost ($)	Max Cost ($)				P50 Estimated Cost ($)
	4,000	7,000	10,000				7,123
WBM with Additives	Min Cost ($/bbl.)	Mean Cost ($/bbl.)	Max Cost ($/bbl.)				P50 Estimated Cost ($)
	20	40	70				83,360
OBM	Min Cost ($/bbl.)	Mean Cost ($/bbl.)	Max Cost ($/bbl.)				P50 Estimated Cost ($)
	70	100	160				171,720
Electro-osmosis Coating	Min Number of Bits	Mean Number of Bits	Max Number of Bits	Min bit Cost ($)	Mean bit Cost ($)	Max bit Cost ($)	P50 Estimated Cost ($)
	2	2.5	3	47,500	55,000	80,000	155,677
Lubricants	Min Volume (bbl.)	Mean Volume (bbl.)	Max Volume (bbl.)	Min Cost ($/bbl.)	Mean Cost ($/bbl.)	Max Cost ($/bbl.)	P50 Estimated Cost ($)
	55	100	200	200	300	400	37,955
Co-polymer Beads	Min Mass (kg)	Mean Mass (kg)	Max Mass (kg)	Min Price ($/kg)	Mean Price ($/kg)	Max Price ($/kg)	P50 Estimated Cost ($)
	6,200	12,400	31,000	3	5	10	89,246
Mechanical Friction	Min Number of Items	Mean Number of Items	Max Number of Items	Min Cost of Item ($)	Mean Cost of Item ($)	Max Cost of Item ($)	P50 Estimated Cost ($)
	10	15	30	2,500	3,000	5,000	56,351
Pressure Pulse Friction	Min Numb	Mean Numbe	Max Number of Items	Min Cost of	Mean Cost of Item ($)	Max Cost of Item ($)	P50 Total Cost ($)

	er of Items	r of Items		Item ($)			
	1	2	5	15,000	25,000	40,000	65,369
Increasing Rig Capabilities	Min Cost of 1 Pipe ($)	Mean Cost of 1 Pipe ($)	Max Cost of 1 Pipe ($)				P50 Total Cost ($)
	500	800	1.000				143,271
Spiral Drill Collars	Min Number of Items	Mean Number of Items	Max Number of Items	Min Cost of Item ($)	Mean Cost of Item ($)	Max Cost of Item ($)	P50 Total Cost ($)
	24	27	30	1,000	3,000	5,000	81,289
RSS	Min Number of Days	Mean Number of Days	Max Number of Days	Min Day Rate ($)	Mean Cost of Item ($)	Max Cost of Item ($)	P50 Total Cost ($)
	15	20	25	3,000	3,500	6,000	60,873

1. Modification in Bit Design- Current bit design includes five different roller cones bits. The total distance drilled with those bits was 1660 m. The new solution in bit design includes a new generation of PDC bits. The parameters affecting the final price are the number of the bits and the price of one PDC bit. General information about bit price is given by Schlumberger, Halliburton, and Weatherford service companies. The number of bits was estimated on the claim provided by those companies that using their PDC bit will give the minimum drilled distance of 1000 m in one run. Therefore, as a minimum number of bits was proposed "2" and the maximum "3".
2. Drilling Hydraulics- The cost estimation includes the daily rate of engineers performing drilling hydraulics calculations. This cost information was given by the INA company.
3. WBM with Additives- The total volume of the drilling fluid system is 1950 bbl. It was drilled with water-based mud. The additives planned to be implemented will help in a fight against shale sticking, agglomeration and accretion problems. The minimum, mean and maximum values were provided by Newpark drilling fluid services in consultation with INA mud engineers. These values refer to how much more 1 barrel of mixed mud costs than the current mud used. The results of these values were calculated based on lower, normal and maximum concentration needed to be mixed in one 1 barrel of mud to effectively stop the encountered drilling problems. The P50 total cost value was estimated using the minimum, mean and maximum values and multiplied with the total volume of mud used in order to get final P50 Total Cost value.
4. OBM- The minimum, mean and maximum price values were set by Mi-Swaco and New park drilling fluid services. These values contain the cost of preparing 1 bbl. of oil-based mud and the disposal of the same mud. Drilling mud needs to be taken

care of after the drilling work is done and with the oil-based mud there could be complications due to strict environmental regulations in Croatia.

5. Electro-Osmosis Coating- Current bit design includes five different roller cones bits. The total distance drilled with those bits was 1660 m. Electro-Osmosis Coating for PDC bit offers bits with minimal drilling distance of 1000 m. They are more expensive than regular PDC bits. The minimum, mean and maximum price information comes from the Haliburton drilling company.
6. Lubricants- The volume of the lubricants was calculated based on the fact that the concentration of lubricants in the mud varies from 3% to 10% depending on how significant the problem is. The total volume of the mud is known, as already mentioned. The lubricants come in different price ranges, depending on the model, and the prices were given by Newpark drilling fluid services. P50 Total Cost was estimated based on changing parameters and by using Monte Carlo simulation.
7. Co-Polymer Beads- In cost estimation for Co-Polymer beads there are two changing parameters. One of them is the mass of co-polymer beads needed to be mixed in the drilling fluid and the second parameter is the price of drilling beads used. The mass used depends on how severe the drilling problem is. It is recommended to use drilling beads in a range from 20 kg/m3 up to 80 kg/m3 of drilling mud. The price of co-polymer beads depends on the model that is going to be used and it is provided by Alpine chemical company.
8. Mechanical Friction Reduction Sub- The number of used items depends on mechanical friction in the wellbore and the total distance to be drilled. The total distance is 1660 m, as already mentioned. A minimal number of items to be used is 15, while the top boundary would be 30. The price depends on the quality of the model used. Price and quantity were estimated by the Rival downhole tools company.
9. Pressure Pulse Reduction Tools- The final price is affected by the number of items used and by the prices of the same items. The number of items depends on mechanical friction in the wellbore and the total distance to be drilled. A minimal number of items is 1 and the maximum is 5. The estimation in the number of items and cost of the same was given by the Impulse Downhole Tools company.
10. Increasing Rig Capabilities- The final price depends on the price of 1 drill pipe going to be used in the new drilling system. The minimum, mean and maximum price was given by the Weatherock group and it depends on the quality of the final product.
11. Spiral Drill Collars- The final price is affected by the number of spiral collars and the price for one item. The number of spiral drill collars was taken by INA’s engineers' team estimation. It is based on the fact that appropriate weight transfer to the bit needs to be implemented in the whole drilling process and to avoid drill pipe buckling.
12. RSS- The final price is affected by the number of days spent in drilling and the daily rate. The distance to be drilled is 1660m and the estimation is that in the best case the drilling would be completed in 15 days, while the worst-case scenario would be 25 days. This information is provided by Weatherford International company. The daily rate price depends on how much time is consumed as a stand by rate and how much by operating rate.

5.3.2 Improved Rate ofPenetration

In the table below all explanations and assumptions for increased drilling efficiency KPIs estimations are stated.

Table 16: Improved Rate of Penetration Estimation

Methods	Min ROP Increase (%)	Mean ROP Increase (%)	Max ROP Increase (%)	P50 ROP Increase (ft/h)
Modification in Bit	15	20	40	4.02
Drilling Hydraulics Modification	5	10	20	1.88
WBM with Additives	5	15	20	2.27
OBM	20	30	40	5.42
Electro-Osmosis Coating	40	70	150	8.73
Lubricants	10	15	25	2.71
Co-Polymer Beads	10	25	30	4.15
Mechanical Friction Reduction Sub	5	15	20	2.26
Pressure Pulse Friction Reduction Sub	15	15	20	2.73
Increasing Rig Capabilities	0	0	0	0
Spiral Drill Collars	0	0	0	0
RSS	30	50	110	8.74

1. Modification in Bit- The information for the needed calculation was gathered from the following papers [33, 34, 47]. Those papers are dealing with bit modification in shale drilling in order to mitigate bit balling. The following conclusion can be made: by implementing new technologies in PDC bit design, ROP in shale drilling will increase in a range from 15% up to 40%.
2. Drilling Hydraulics Modification- The information for the needed calculation was gathered from the following paper [35] which explains a new drilling hydraulics design. The research done by that paper states that by improving hydraulics design, ROP will increase in a range from 5% up to 20%.
3. WBM with Additives- Bit- The information for the needed calculation was gathered from the following papers [36, 37]. These papers are dealing with additives that are added into water-based mud in order to prevent shale sticking, agglomeration, and accretion. The conclusion is that by adding those additives, ROP will increase in a range from 5% up to 20%.
4. OBM – The information for the needed calculation was gathered from the following papers [13, 48]. These papers are dealing with oil-based mud and with the effect of

drilling fluid properties on improving ROP in shale. It is concluded that by using an oil-based mud system, ROP could increase in a range from 20% up to 50%.

5. Electro-Osmosis Coating- The information for the needed calculation was gathered from the following papers [4, 12, 38]. These papers are dealing with introducing new technology in drilling a shale. It is an electro-osmosis coating that helps in solving bit balling problems. The following conclusion can be made: by implementing this technology, ROP will increase in a range from 40% up to 150%.
6. Lubricants- The information for the needed calculation was gathered from the following papers [39, 40], which are dealing with new, enhanced lubricants that reduce friction factor and therefore help in a fight against high torque and drag problem. The conclusion is that by using lubricants in a drilling fluid system, ROP will increase in a range from 10% up to 25%.
7. Co-Polymer Beads- The information for the needed calculation was gathered from the following papers [41, 42]. These papers deal with using co-polymer beads in directional and horizontal operations to reduce torque and drag and to improve ROP. The following conclusion can be made: by implementing co-polymer beads in a drilling fluid system, ROP will increase in a range from 10% up to 30%.
8. Mechanical Friction Reduction Sub- The information for the needed calculation was gathered from the following papers [43, 44] which deal with mechanical friction reduction tools in horizontal and directional operations. The conclusion from these papers is that by implementing this drilling technique, ROP will increase in a range from 5% up to 20%.
9. Pressure Pulse Friction Reduction Sub- The information for the needed calculations was obtained from the Downhole Tool International company. They are claiming that by using pressure pulse friction reduction sub in horizontal wells, ROP will increase in a range from 15% up to 20%.
10. Increasing Rig Capabilities- INA engineer's team and the author agreed that by exchanging old drilling pipes with the new ones, will not affect ROP.
11. Spiral Drill Collars- INA engineer's team and the author agreed that usage of spiral drill collars instead of regular drill collars will not change ROP.
12. RSS- The information for the needed calculation was gathered from the following papers [19, 45, 46]. These papers are dealing with rotary steerable system application in horizontal shale wells. The following conclusion can be made: by implementing RSS in horizontal shale wells instead of PDM motors, ROP will increase in a range from 30% up to 110%.

5.3.3 Operational Simplicity

In the table below all explanations and assumptions for operational simplicity KPIs estimations are stated.

Table 17: Operational Simplicity Estimation

Methods	Rating 1-20
Modification in Bit	17
Drilling Hydraulics Modification	19
WBM with Additives	14
OBM	4
Electro-Osmosis coating	17
Lubricants	13
Co-Polymer Beads	12
Mechanical Friction Sub	18
Pressure Pulse Friction Sub	16
Increasing Rig Capabilities	20
Spiral Drill Collars	20
RSS	18

1. Modification in Bit – This method is rated with "17". It is pretty simple to operate with a PDC bit, the only thing to care is while making BHA and to apply appropriate WOB during drilling operations.
2. Drilling Hydraulics Modification – Calculations need to be performed and nozzles need to be changed. It is a very routine operation.
3. WBM with Additives – It is very important to choose correct additives to reduce bit balling, otherwise, it could even make the whole situation even worse. During mixing mud with additives, extra care needs to be implemented because of toxic and possible flammable substances. But in total, there is a wide source of treating an agent, multiple types available for selection and easy control of performance.
4. OBM – It was graded with "4" meaning it is a pretty complicated technique. This is because of volatile components in mud can easily cause fire, excessive treatment of OBM is required due to toxic components. Bulk discharge of drilling fluid is prohibited due to environmental regulations.
5. Electro-Osmosis Coating – It is rated with "17". The drilling procedures are similar to the bit modification method.
6. Lubricants – It is rated with "13". The reason for that is the need to use the correct lubricant or the lubricant work will not work. If the wrong lubricant is applied or used, the functions are unlikely to be carried out efficiently; which can result in seizure, overheating, damages. Disposal of lubricants has to be done well to prevent serious environmental contamination.
7. Co-Polymer Beads – It is rated with "12". It was grated as a little bit complicated than using lubricants because it is very toxic and conventional solids control equipment needs to be adjusted to discharge drilling beads out from the mud system.

8. Mechanical Friction Reduction Sub – It is rated with "18". It is adjusted on the surface. No special care is needed to use this method. It is pretty easy to handle, but it is a relatively new technique and that is why is graded with this number.
9. Pressure Pulse Reduction Sub – It is activated via drop ball from the surface. It has an adjustable operating frequency and it is a little bit more complicated than mechanical friction reduction sub and that is why it is rated with "16".
10. Increasing Rig Capabilities – It is rated with "20", meaning it is a very simple operation. Old drilling pipes are replaced with the new one.
11. Spiral Drill Collars – It is also rated with "20". Instead of classic drill collars, spiral drill collars are going to be used. It is not a new technique and it is very simple to operate with it.
12. RSS – It rated with "18". This is because in this case a team of expertise needs to be hired to accomplish this method and they have a lot of experience in this, so it is rated with that number as a quite simple operation.

5.3.4 Improved Wellbore Stability

In the table below all explanations and assumptions for improved wellbore stability KPIs estimations are stated. All KPI's were set based on INA's engineer team opinion.

Table 18: Improved Wellbore Stability Estimation

Methods	Rates 1-20
Modification in Bit	10
Drilling Hydraulics Modification	14
WBM with Additives	17
OBM	19
Electro-Osmosis coating	11
Lubricants	14
Co-Polymer Beads	6
Mechanical Friction Sub	12
Pressure Pulse Friction Sub	12
Increasing Rig Capabilities	0
Spiral Drill Collars	10
RSS	14

1. Modification in Bit – It is rated with "10". This rating was estimated in consultation with INA engineers. It is based on the fact that modification in the bit will only slightly improve wellbore stability by improving the wellbore hole quality.
2. Drilling Hydraulics Modification – With adjusting hydraulics, erosion of the wellbore can be reduced and wellbore stability improved.
3. WBM with Additives – It has great potential to improve wellbore stability. Additives will directly work on mud temperature, erosion of the wellbore and rock fluid interaction. It will stop shale swelling.
4. OBM – It has great potential for improving wellbore stability. It directly cools down the bit, prevents shale from swelling and supports the shale formation and its oil molecules cannot penetrate into tiny organic and non-organic pores under the capillary pressure.

5. Electro-Osmosis Coating – It is rated with "11". This is because it has similar features as bit modification, but electro-osmosis coating will stop the bit from balling and this way leads to improved wellbore stability.
6. Lubricants – It is rated with "14" because it has a lower effect on improving wellbore stability than WBM with additives. It works in a way that promotes a hydrophobic coating on both the bit and drill cuttings and this way improves wellbore stability.
7. Co-Polymer Beads – It has some of the benefits for improving wellbore stability such as improved wellbore conditions, reduced differential sticking problems and reduced metal-to-metal friction are benefits. It is rated only with "6" because there is a possible major solid build up if the beds are not properly removed.
8. Mechanical Friction Reduction Sub – This method will decrease drill string vibrations and this way lead to increased wellbore stability.
9. Pressure Pulse Reduction – It has the same rating as a mechanical friction sub because it has a similar effect on improving wellbore stability.
10. Increasing Rig Capabilities – This method will have zero impact on improving wellbore stability.
11. Spiral Drill Collars – This method is rated the same as bit modification. It has a similar effect on wellbore stability. This method will affect differential sticking problems.
12. RSS – This method will lead to better hole cleaning, improved wellbore hole quality, reduced tortuosity. By those criteria, it is rated with "14".

The following KPIs are related to the probability of success method.

5.3.5 NPT Reduction Savings

In the table below, savings potential based on NPT reduction is being calculated. NPT Reduction column has three different times represented. Time reduction of 62 h stands for bit balling problem, 88 h stands for high torque & drag problem and 54 h stands for stuck pipe problem. NPT Reduction column is being multiplied with the rig rate column in order to get potential savings for different methods being implied.

Table 19: NPT Reduction Savings

Drilling Methods	NPT Reduction (h)	Rig Rate ($/h)	Savings ($)
Drilling Hydraulics Modification	62.0	900	55,800
WBM with Additives	62.0	900	55,800
Bit Modification	62.0	900	55,800
Electro-Osmosis Coating	62.0	900	55,800
OBM	62.0	900	55,800
Lubricants	88.0	900	79,200
Co-Polymer Beads	88.0	900	79,200
Mechanical Friction Reduction Sub	88.0	900	79,200
Pressure Pulse Reduction Sub	88.0	900	79,200
Increasing Rig Capabilities	88.0	900	79,200

RSS (High Torque and Drag)	88.0	900	79,200
Spiral Drill Collars	54.0	900	32,400
RSS (Stuck Pipe)	54.0	900	32,400

5.3.6 Improved Rate of Penetration Savings

In the table below, an improved rate of penetration KPIs results is shown. Average ROP was calculated based on distance drilled and time spent to drill that distance. "P50 ROP Increase (ft/h)" values were taken from the "Improved Rate of Penetration" table. Based on that, the biggest savings potential for bit balling shows electro-osmosis coating (101,700). The RSS method shows the biggest savings potential for high torque & drag and stuck pipe problem (101,700 $).

Table 20: Improved Rate of Penetration Savings

Drilling Methods	Average ROP (ft/h)	P50 ROP Increase (ft/h)	Length Drilled (ft)	Time Saved (h)	Rig Rate ($/h)	Savings ($)
Drilling Hydraulics Modification	16.6	1.88	5,450	34	900	30,600
WBM with Additives	16.6	2.27	5,450	40	900	36,000
Bit Modification	16.6	4.02	5,450	64	900	57,600
Electro-Osmosis Coating	16.6	8.73	5,450	113	900	101,700
OBM	16.6	5.42	5,450	81	900	72,900
Lubricants	16.6	2.71	5,450	46	900	41,400
Co-Polymer Beads	16.6	4.15	5,450	66	900	59,400
Mechanical Friction Reduction Sub	16.6	2.26	5,450	40	900	36,000
Pressure Pulse Reduction Sub	16.6	2.73	5,450	47	900	43,300
Increasing Rig Capabilities	16.6	0.00	5,450	0.0	900	0.0
RSS	16.6	8.74	5,450	113	900	101,700
Spiral Drill Collars	16.6	0.00	5,450	0.0	900	0.0

5.4 Weighted Matrix Method

The weighted matrix method will be used on the three problems that were presented by NPT distribution shown in Figure 37. These problems include bit balling, high torque & drag and stuck pipe.

5.4.1 Bit balling

Table 21 shown below shows already estimated KPIs: "Additional Incurred Cost, Improved Rate of Penetration, Operational Simplicity and Improved Wellbore Stability".

Table 21: Bit Balling Weighted Matrix KPIs

Bit Balling				
Methods	**Additional Incurred Cost**	**Improved Rate of Penetration**	**Operational Simplicity**	**Improved Wellbore Stability**
	$	ft/h	Grade	Grade
Modification in Bit	120,029	4.02	17	10
Drilling Hydraulics Modification	7,123	1.88	20	14
WBM with Additives	83,360	2.27	14	17
OBM	171,720	5.42	4	19
Electro-Osmosis Coating	155,677	8.73	15	11
	Min	Max	Max	Max
	7,123	8.73	20	19

Table 22: Bit Balling Weighted Matrix Final Score

	Additional Incurred Cost	**Improved Rate of Penetration**	**Operational Simplicity**	**Improved Wellbore Stability**	
	Weighted factor				Score
Methods	2	3	1	2	8
Modification in Bit	0.12	1.38	0.85	1.05	3.5
Drilling Hydraulics Modification	2.00	0.65	1.00	1.47	5.1
WBM with Additives	0.17	0.78	0.70	1.79	3.4
OBM	0.08	1.86	0.20	2.00	4.1

Electro-Osmosis Coating	0.09	3.00	0.75	1.16	5.1

Table 22 shows the weighted factor criteria for each KPI presented. For instance, "Additional Incurred cost" has been assigned with the weighted factor "2", while "Operational Simplicity" KPI is not that important and it is assigned with the weighted factor "1". In this table, a weighted score calculation can also be seen. For instance, OBM has weighted score for "Additional Incurred Cost" KPI "0.08", while for "Improved Wellbore Stability" has "2.0" as a score.

When all weighted scores are summarized, the final score is as follows. The drilling methods that produce the best score against bit balling are Electro-Osmosis coating and Drilling Hydraulics Modification (score 5.1), followed by OBM (score 4.1), Modification in Bit (3.5), and WBM with as the least efficient methods with the same score of High Torque and Drag

5.4.2 High Torque & Drag

During the drilling process, the drilling crew has had quite a lot of problems with high torque and drag. Based on set KPIs and weighted matrix estimation, RSS (7.2) showed as the best method, followed by Lubricants (5.7), Mechanical Friction Reduction Sub (4.8), Pressure Pulse Reduction Sub (4.7), Co-Polymer Beads (3.8), and in the last place Increasing Rig Capabilities (1.5).

Table 23: High Torque & Drag Weighted Matrix KPIs

High torque and Drag				
	Additional Incurred Cost	Improved Rate of Penetration	Operational Simplicity	Improved Wellbore Stability
Methods	**$**	**ft/h**	**Grade**	**Grade**
Lubricants	37,955	2.71	13	14
Co-Polymer Beads	89,246	4.15	12	6
Mechanical Friction Reduction Sub	56,351	2.26	18	12
Pressure Pulse Friction Reduction Sub	65,369	2.73	16	12
Increasing Rig Capabilities	143,271	0.00	17	0
RSS	60,873	8.74	18	14
	Min	**Max**	**Max**	**Max**

	37,955	8.74	18.00	14.00

Table 24: High Torque & Drag Weighted Matrix Final Score

	Additional Incurred Cost	Improved Rate of Penetration	Operational Simplicity	Improved Wellbore Stability	
	Weighted factor				Score
Methods	2	3	1	2	8
Lubricants	2.00	0.93	0.72	2.00	5.7
Co-Polymer Beads	0.85	1.42	0.67	0.86	3.8
Mechanical Friction Reduction Sub	1.35	0.78	1.00	1.71	4.8
Pressure Pulse Friction Reduction Sub	1.16	0.94	0.89	1.71	4.7
Increasing Rig Capabilities	0.53	0.00	0.94	0.00	1.5
RSS	1.25	3.00	1.00	2.00	7.2

5.4.3 Stuck Pipe

Stuck pipe problems have two solutions. Weighted matrix method expressed RSS as a much better option with 7.9 points in total, while spiral drill collars gaveonly 3.9 points in total.

Table 25: Stuck Pipe Weighted Matrix KPIs

Stuck pipe				
Methods	Additional Incurred Cost	Improved Rate of Penetration	Operational Simplicity	Improved Wellbore Stability
	$	**ft/h**	**Grade**	**Grade**
Spiral Drill Collar	81,289	0	20	10
RSS	60,873	8.74	18	14
	Min	**Max**	**Max**	**Max**
	60,873	8.74	20	14

Table 26: Stuck Pipe Weighted Matrix Final Score

	Additional Incurred Cost	Improved Rate of Penetration	Operational Simplicity	Improved Wellbore Stability	
	Weighted factor				Score
Methods	2	3	1	2	8
Spiral Drill Collar	1.50	0.00	1.00	1.43	3.9
RSS	2.00	3.00	0.90	2.00	7.9

5.5 Probability of Success Method

In the following lines, the probability of success method will bring the results of the evaluated drilling methods for the evaluation decision-making process. All KPIs used are explained in chapter 4, KPI section.

5.5.1 Bit Balling

Table 27 represents the P50 estimations of negative KPIs and positive KPIs. Total expenditure and total savings will be used in the following probability of success method estimation.

Table 27: P50 Total Expenditure and Total Savings Potential for Bit Balling

NKPIs	Drilling Hydraulics Modification	WBM with Additives	Bit Modificationtion	Electro-Osmosis Coating	OBM
Additional Incurred Cost	7,123 USD	83,360 USD	120,029 USD	156,667 USD	171,720 USD
Total Expenditure	7,123 USD	83,360 USD	120,029 USD	156,667 USD	171,720 USD
PKPIs					
NPT Reduction Savings	55,800 USD	55,800 USD	55,800 USD	55,800 USD	55,800 USD
Improved Rate of Penetration Savings	30,600 USD	36.000 USD	57.600 USD	101,070 USD	72,900 USD
Total Savings	86,400 USD	91,800 USD	113,400 USD	156,870 USD	128,700 USD

The picture below shows six graphs for each of the following methods: Lubricants, Co-Polymer Beads, Mechanical Friction Reduction Sub, Increasing Rig Capabilities, Pressure Pulse Reduction Sub, and RSS. Graphs were designed using table 27 "Total Expenditure" and "Total Savings" values.

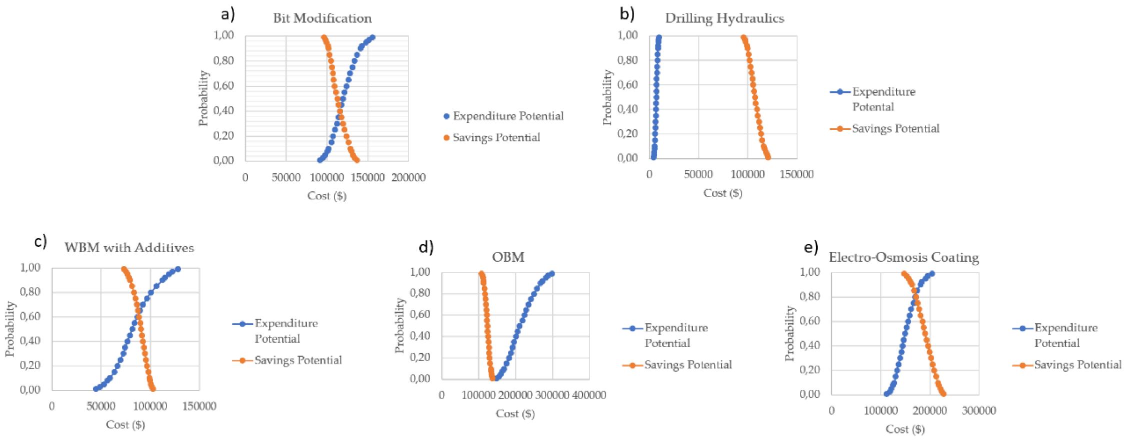


Figure 36: Bit Balling Probability of Success

For all of these methods, the interception point (point in which the expenditure and savings potential line meet) can be seen. Bit modification (a) has an interception point at 0.35, which means that the probability that the required cost for this solution will equal the savings cost is 35%. For drilling hydraulics, the expenditure potential and savings potential lines do not cross and expenditure potential line has way lower values than savings potential line, meaning that the probability that the required cost for this solution will equal the savings cost is 100%. For WBM with Additives (c) that point lies at 0.6, meaning a probability that the required cost for this solution will equal the savings cost is 60 %. For OBM (d) method's interception point is at 0.01, meaning the probability that the required cost for this solution will equal the savings cost is only 1%. Finally, Electro-Osmosis Coating (e) method has an interception point at 0.85, which means that the probability that the required cost for this solution will equal the savings cost is 85%.

In conclusion, the best method to choose would be Drilling Hydraulics, based solely on the probability of success method, because of its highest percentage (100%).

5.5.2 High Torque & Drag

In the table below all the KPIs can be found calculated, an explanation for them can be found in chapter 4, KPI section.

Table 28: Total Expenditure and Total Savings Potential for High Torque and Drag

NKPIs	Lubricants	Co-Polymer Beads	Mechanical Friction Reduction Sub	Pressure Pulse Reduction Sub	Increasing Rig Capabilities	RSS
Additional Incurred Cost	37.955 USD	89.246 USD	56.351 USD	65.369 USD	143.271 USD	60.873 USD

Operational Adjustment Expenses	12.079 USD	15.317 USD	20.349 USD	15.088 USD	0 USD	6.010 USD
Downhole Impact	22.019 USD	4.660 USD	0 USD	0 USD	0 USD	21.843 USD
Total Expenditure	72.052 USD	109.223 USD	76.700 USD	80.457 USD	143.271 USD	88.725 USD
PKPIs						
NPT Reduction Savings	50.915 USD	47.685 USD	33.575 USD	41.055 USD	70.040 USD	65.365 USD
Improved Rate of Penetration Savings	39.323 USD	55.972 USD	33.599 USD	39.572 USD	0 USD	96.411 USD
Additional Improving Savings	0 USD	6.379 USD	0 USD	0 USD	3.541 USD	6.430 USD
Total Savings	90.238 USD	110.036 USD	68.982 USD	80.627 USD	73.581 USD	168.206 USD

The picture below shows six graphs for each of the following methods: Lubricants, Co-Polymer Beads, Mechanical Friction Reduction Sub, Increasing Rig Capabilities, Pressure Pulse Reduction Sub, and RSS. Graphs were designed using table 28 "total expenditure" and "total savings" values.

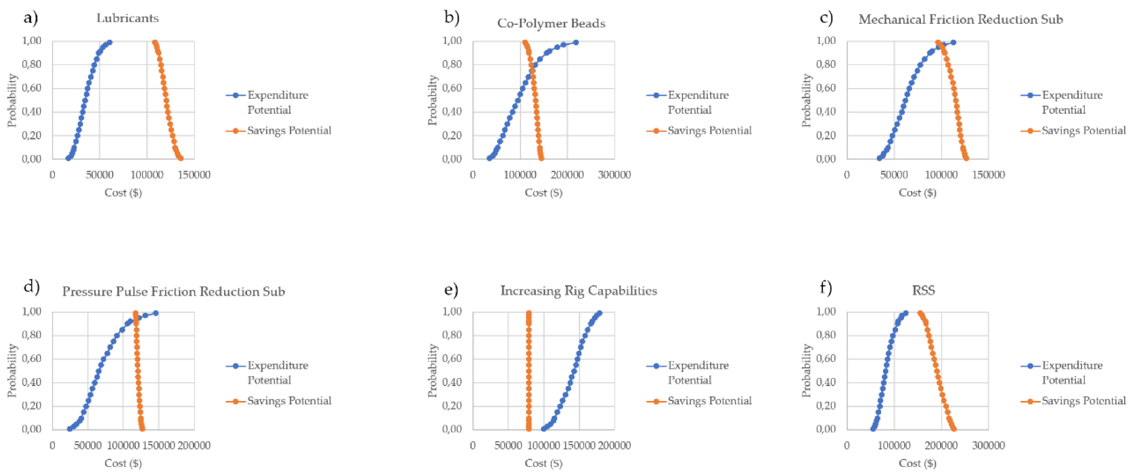


Figure 37: High Torque & Drag Probability of Success

For all of these methods, the interception point (point in which the expenditure and savings potential line meet) can be seen. For Lubricants (a) the expenditure potential and savings potential lines do not cross and expenditure potential line has way lower values than savings potential line, meaning that the probability that the required cost for this solution will equal the savings cost is 100%. For Co-Polymer Beads (b) that point lies at 0.75, meaning a probability that the required cost for this solution will equal the savings cost is 75%. Mechanical Friction Reduction Sub (c) lines intercept at 0.92, showing that the probability that the required cost for this solution will equal the savings cost is 92%. Pressure Pulse Reduction Sub (d) method has an interception point at 0.90, which means that the probability that the required cost for this solution will equal the savings cost is 90%. Increasing Rig Capabilities (e) method has an interception point at 0.00, which means that a probability that the required cost for this solution will equal the savings cost is 0 %.

At last, for RSS (f) the expenditure potential and savings potential lines do not cross and expenditure potential line has way lower values than savings potential line, meaning that the probability that the required cost for this solution will equal the savings cost is 100%.

In conclusion, the best methods to choose would be Lubricants and RSS, based solely on the probability of success method, because of its highest percentage (100%).

5.5.3 Stuck pipe

In the table below all the KPIs can be found calculated, an explanation for them can be found in chapter 4, KPI section.

Table 29: Total Expenditure and Total Savings Potential for Stuck Pipe

NKPIs	Spiral Drill Collars	RSS
Additional Incurred Cost	81.289 USD	60.873 USD
Operational Adjustment Expenses	12.946 USD	6.010 USD
Downhole Impact	5.265 USD	21.843 USD
Total Expenditure	99.499 USD	88.725 USD
PKPIs		
NPT Reduction Savings	18.360 USD	40.120 USD
Improved Rate of Penetration Savings	0 USD	96.411 USD
Additional Improving Savings	37.400 USD	31.675 USD
Total Savings	55.760 USD	168.206 USD

The picture below shows two graphs for Spiral Drill Collars and RSS method. Graphs were designed using table 29 "total expenditure" and "total savings" values.

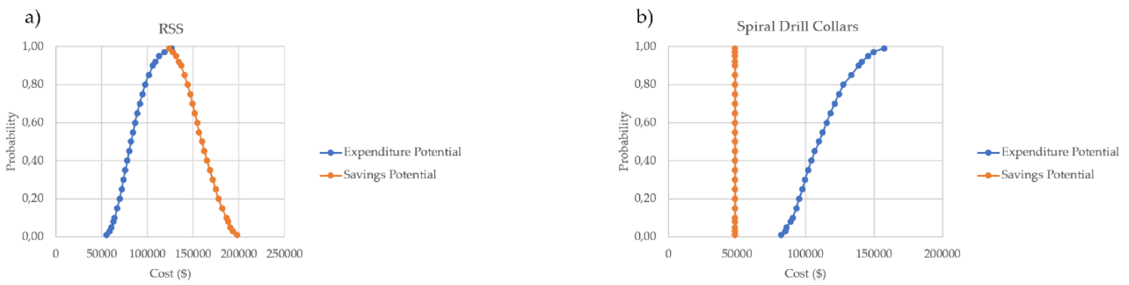


Figure 38: Stuck Pipe Probability of Success

For all of these methods, the interception point (point in which the expenditure and savings potential line meet) can be seen. For RSS method (a) has an interception point at 0.97, which means that probability that the required cost for this solution will equal the savings cost is 97%. For Spiral Drill Collars (b) the expenditure potential and savings potential lines do not cross and expenditure potential line has way higher values than the savings potential line, meaning that the probability that the required cost for this solution will equal the savings cost is 0%.

In conclusion, the best method to choose would be RSS, based solely on the probability of success method, because of its highest percentage (97%).

5.6 Integrated Approach

5.6.1 Bit Balling

To do the integrated approach method, both, the weighted matrix score and the probability of success were divided into low and high values, with 4 and 0.5 being the borderline for the weighted matrix score and the probability of success, respectively. This means all of the values under 4 and 0.5 are considered low value, and values above that are considered high value. For example, OBM has a high weighted matrix score 4.1 but an extremely low probability of success 1%, thus making it a method that would fall into a category off least successful method. Drilling Hydraulics with weighted matrix score 5.1 and probability of success 100% makes this method the most desirable option (Table 30 and Figure 41).

Table 30: Bit Balling Integrated Approach

Methods	Weighted Matrix Score	Probability of Success
Drilling Hydraulics	5.1	1.00
WBM with Additives	3.4	0.60
Bit Modification	3.4	0.35
Electro-Osmosis Coating	5.0	0.85
OBM	4.1	0.01

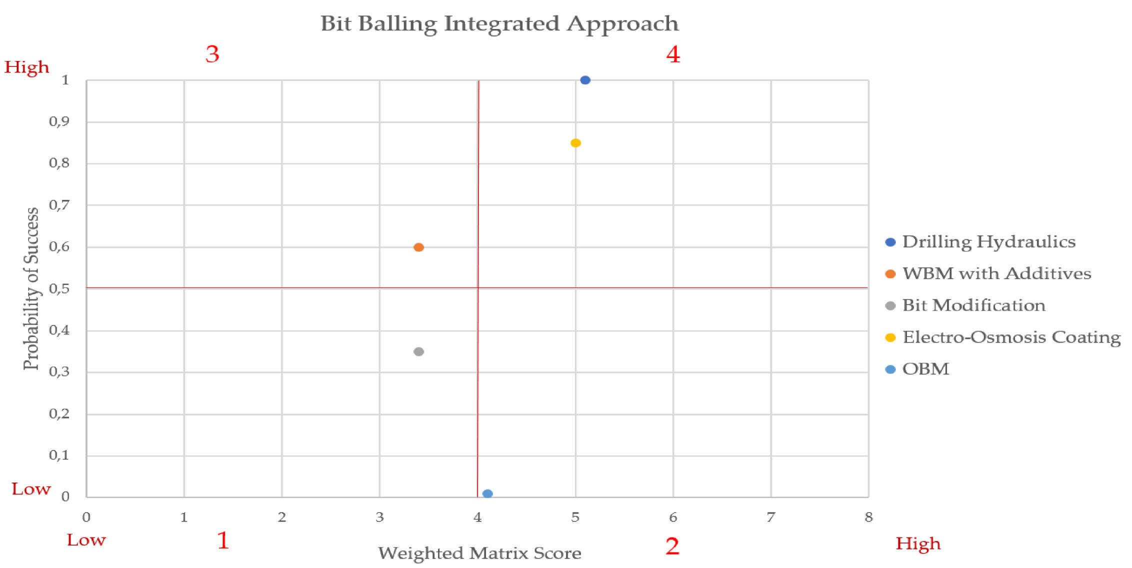


Figure 39: Bit Balling Integrated Approach

5.6.2 High Torque and Drag

Table 29 represents the final weighted matrix and probability of success method results for the high torque and drag problem.

Table 31: High Torque & Drag Integrated Approach

Methods	Weighted Matrix Score	Probability of Success
Lubricants	5.7	1.00
Co-Polymer Beads	3.8	0.75
Mechanical Friction Reduction Sub	4.8	0.92
Pressure Pulse Reduction Sub	4.7	0.90
Increasing Rig Capabilities	1.5	0.00
RSS	7.2	1.00

Results of the weighted matrix method and the probability of success are showing that RSS is performing the best against high torque and drag problem since it falls into section 4 (high-high). RSS has a weighted matrix score of 7.2 and probability of success 100% which is clearly the best method (Figure 42).

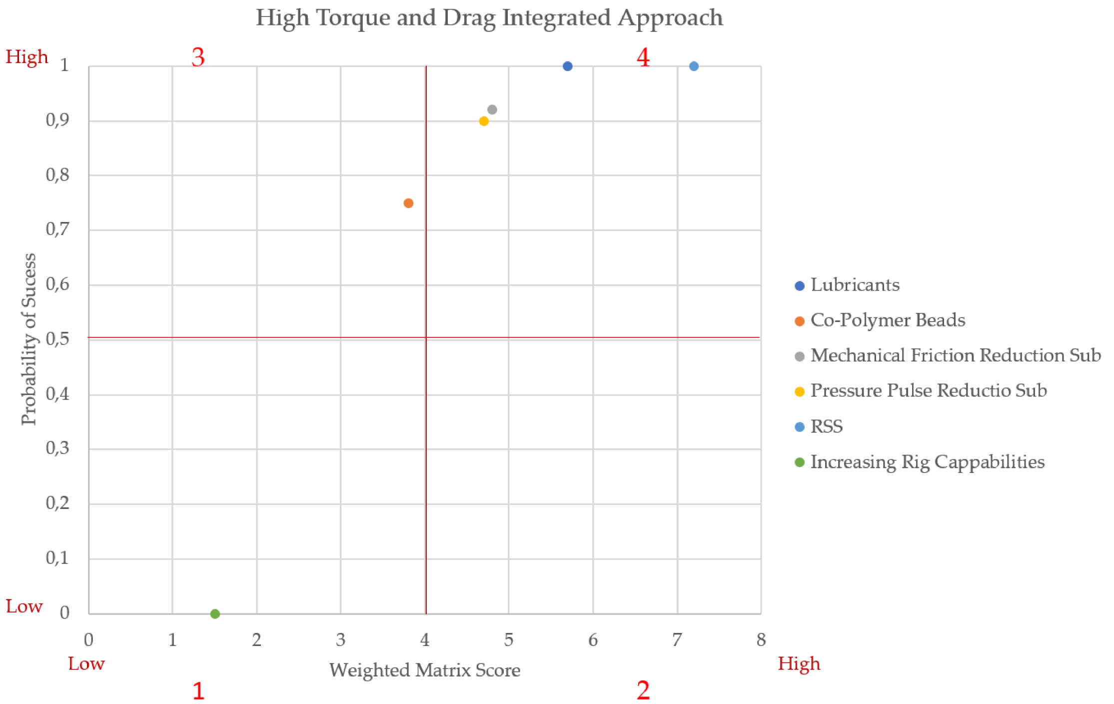


Figure 40: High Torque & Drag Integrated Approach

5.6.3 Stuck Pipe

Table 30 shows the final results for the stuck pipe problem of the weighted matrix method and probability of success method.

Table 32: Stuck Pipe Integrated Approach

Methods	Weighted Matrix Score	Probability of Success
Spiral Drill Collars	3.9	0.00
RSS	7.9	0.97

Stuck pipe problem is offering only two solutions. RSS performed much better and showed better results in the evaluation process. RSS has a weighted matrix score of 7.9 and a probability of success 97% which makes it clearly a better option in the fight against the stuck pipe problem (Figure 43).

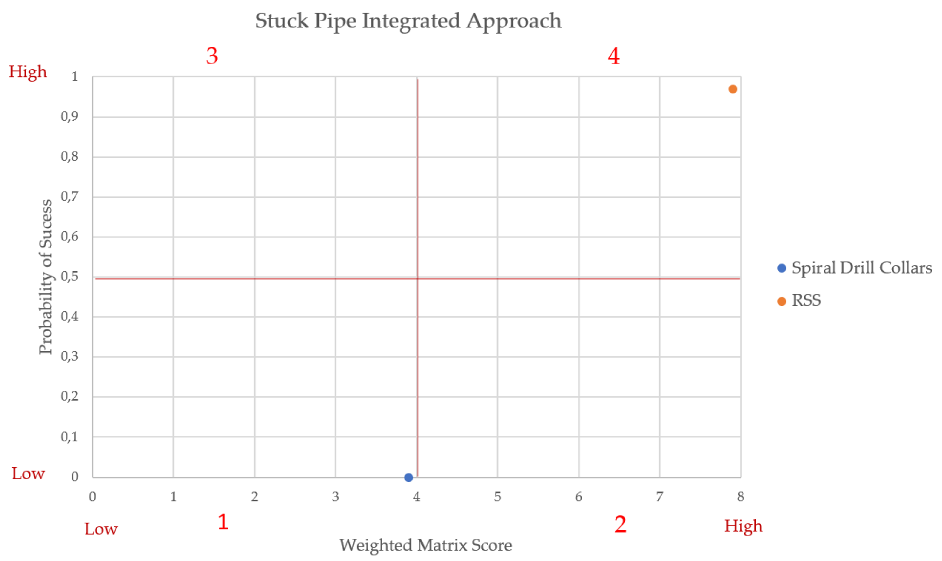


Figure 41: Stuck Pipe Integrated Approach

5.7 Case Study Conclusion

In order to evaluate the drilling performance and to choose the best methods for re-entry drilling, it is very important to collect all data available, produced during the drilling process, regardless of whether they are meta or sensor data. Collected data will reduce the rate of uncertainty in the final assessment.

Additionally, collected data were analyzed for the purpose of getting non-productive time, setting the basis for further work on the case study. Non-productive time analysis produces three main root causes. Those are bit balling, high torque & drag, and stuck pipe. Given results were fundamental to propose the best methods for each main of the NPT root cause problems. Assumed solutions were evaluated based on two different tools. The first estimation tool was the weighted matrix method. The limitation of this tool lies in the fact that the final solution is tightly connected with the uncertainty in different parameters and weighted factors that are set based on the INA engineer's experience. This means that the final weighted matrix method solution is mostly based on personal opinion and quite subjective.

To enhance the decision-making process different decision tool was presented, the probability of success method. This tool brings the final decision based on two sets of KPI's. Those are positive and negative KPI's expressed as a cost unit and based on them the final decision is being brought.

When these two tools were combined together, they produced an integrated approach solution for each root problem cause of NPT. Based on the given results, the best method for bit balling is drilling hydraulics; high torque & drag and stuck pipe share the same solution and that solution is the rotary steerable system. Most of the calculations and assumed parameters for decision-making tools have been done with the cooperation of INA's engineers.

Chapter 6 Conclusion

The objectives of the thesis were to:

- Familiarize the reader with the drilling problems that occurred during re-entry drilling
- Analyze the well in terms of NPT, identify major NPT events and their root causes and quantify the amount of NPT
- Propose a different solution to the occurring problems
- Come up with a decision-making process to decide the best method for each problem

Currently used drilling methods come with a lot of problems that cause money loss. That's why it's important to do preplanning and use concepts that can estimate which method would be the most efficient. In most preplanning scenarios, the weighted matrix method is used. This method assigns scores to drilling methods based on different parameters involved in the decision-making process. The challenge with this method is that the parameters come with uncertainty, since they are estimated by humans and the final score is based on their personal opinion, therefore they can vary depending on the company giving the data and the analyst. To make the estimation stronger, drilling methods alternatives were also evaluated by the probability of success method. With this method, calculations were made as a percentage of chance that some method will be successful. This percentage comes as a result of data extracted from other similar scientific articles, meaning it is based on previous experience established in the oil and gas business.

The case study, presented in this thesis, deals with these two methods, and in the end combines them in an integrated approach, which points out to the most efficient method based on a score given by WM and probability given by POS. The integrated approach was tested for a real case scenario to evaluate different proposed drilling methods considering the root cause of NPT, during constructing the sidetrack well W1-JR.

The integrated approach has shown as a good alternative to used methods in an evaluation process. Although it is not the most reliable approach, it is certainly better to use two different evaluating methods integrated into one approach, instead of just using one, since the unreliability of parameters is reduced. There is still some room left for improvement. To get a more trustworthy output, input data should be more precise. In a case study, there were a lot of uncertainties and a lot of estimations. To ensure good results of an integrated approach more detailed information from other offset wells should be available. The multidisciplinary approach and teamwork of geophysics, geologist, reservoir, production and drilling engineers is a necessary precondition for maximum trustworthy results.

References

1. Eric van Oort, SPE, Shell E&P Technology. "Physico-Chemical Stabilization of Shales", SPE 37263, 1997.
2. Van Oort, E. "On the Physical and Chemical Stability of Shales." Journal of Petroleum Science and Engineering, v38, (2003) 213-235.
3. Sideney J. Green, Arnis Judzis, David Curry, "Single Cutter Testing Improves Undertanding of Deepwater Hammer Drilling Performance", SPE 97173-MS, 2005
4. G.A. Cooper', Sanjit Roy, "Prevention of Bit Balling by Electro-Osmosis", SPE 27882, 1994
5. G. De Stefano, Shrieve Chemicals, S. Young, M-I Swaco, "The Prevention and Cure of Bit Balling in Water Based Drilling Fluids", OMC, 2009
6. P.R. Hariharan and G.A. Cooper, U. of California, and A.H. Hale, * Shell E&P Technology Co. *IADC Mem, "Bit Balling Reduction by Electro-Osmosis While Drilling Shale Using a Model BHA (Bottom Hole Assembly)", SPE 39311, 1998
7. D.H. Zijsling, Eggbeater PDC Drillbit Design Eliminates Balling in Water Based Drilling Fluids", SPE, 1993
8. M.J. Fear, "An Expert System for Drill Bit Selection", SPE 27470, 1994
9. M. Wells, T. Marvel, C. Buershauesn, H, Christensen, a Baker Hughes company, "Bit Balling Mittigation in PDC Bit Design", SPE 114673, 2008
10. Smith, L., Mody, F.K., Hale, A., and Romslo, N. "Successful Field Application of an Electro-Negative Coating to Reduce Bit Balling Tendencies in Water Based Mud." SPE 35110, SPE/IADC Drilling Conference, New Orleans, March 12-15, 1996.
11. R. Bland, T. Jones, "Reducing Drilling Cost by Drilling Faster", SPE 38616, 1997
12. P.R. Hariharan and G.A. Cooper, U. of California, and A.H. Hale,* Shell E&P Technology Co. *IADC Mem, "Bit Balling Reduction by Electro-Osmosis While Drilling Shale Using a Model BHA (Bottom Hole Assembly)", SPE 39311, 1998
13. Eric van Ooort, M. Ahmad, The University of Texas at Austin;R. Spencer, Baker Hughes, "ROP Enhancement in Shales through Osmotic Processes", 2015
14. Young, S. et al. "Organo-Amine Chemistry – An Innovative Key to Achieving Invert Emulsion Performance with Water- Based Drilling Fluids." SPE 80275, SPE Oilfield Chemistry Symposium, Houston, February 5-8, 2003.
15. Warren, T. M. and Armagost, "Laboratory Drilling Performance of PDC Bits," SPE Drillin g Engineering. June 1988
16. McCormick J.E., Evans C.D., Le J., Chiu T., "The Practice and Evolution of Torque and Drag Reduction: Theory and Field Results," 2012 International Petroleum Technology Conference held in Bangkok, Thailand, 7-9 February 2012, IPTC 14863.
17. Johancsik, C.A., Friesch, D.B., and Dawson, R. "Torque and Drag in Directional Wells-Prediction and Measurement". Journal of Petroleum Technology 36: 987-992., 1984

18. WiperTrip Drilling and Well Engineering Resources, www.wipertrip.com/stuck-pipe/causes/363-mechanical-sticking-cause-of-stuck-pipe.html, last visited on October 2018
19. J. Sugiura, S. Jones, PathFinder Energy Services, “Rotary Steerable System Enhances Drilling Performance on Horizontal Shale Wells”, SPE 131357, 2010
20. J. Maehs, S. Renne, B. Logan, Appache Corporation, Baker Hughes, “Proven Methods and Techniques to Reduce Torque and Drag in the Pre-Planning and Drilling Execution of Oil and Gas Wells”, SPE 128329, 2011
21. Agbaji, Armstrong L. *et al*.: “Optimizing the Planning, Design and Drilling of Extended Reach and Complex Wells” paper SPE 136901 presented at the Abu Dhabi International Petroleum Conference, Abu Dhabi, UAE., 1-4 November 2010.
22. Bone, Glenn. *et al*.: “Mature Field Benefits from Application of High-End Technology” paper SPE 92624 presented at the SPE/IADC Drilling Conference, Amsterdam, The Netherlands., 23-25 February 2005.
23. Chilingarian G.V., Vorabutr P. Drilling and drilling fluids
24. M.S. Farahat Drilling problems; 1992
25. Azar J.J and Samuel, 2007, Drilling Engineering
26. Lake, Larry W. 2005. Petroleum Engineering Handbook
27. Bailey etal. 1991, Problems and solutions.
28. Qadir Tunio etal, 2011 Is It Possible to Ignore Problems Rising During Vertical Drilling? A Review
29. Islam A. 2009, Underbalanced Drilling in Shale (UDB) - Perspective of Factors Influences Mechanical Borehole Instability
30. Anadrill Schlumberger 1997, Stuck Pipe Self Learning Course
31. International Journal for Research in Applied Science & Engineering Technology (IJRASET) ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor:6.887 Volume 5 Issue VIII, August 2017- Available at www.ijraset.com ©IJRASET (UGC Approved Journal): All Rights are Reserved 64 Powered Rotary Steerable System Technology B.Antony Fayaz1 ,Govindan.S2 1,2 Department of Petroleum Engineering, AMET University, Chennai -603112
32. DRILL COLLAR STRING DESIGN AND ITS EFFECT ON DRILLING M.E.R. By Fred K. Fox, Member ATh1E, and Nadim Nasir, Engineering Enterprises, Inc., Houston, Texas
33. Dr. Michael Wells, PLUERE, Inc:Tim Marvel, Chad Beuershausen, and Baker Hughes company, “Bit Balling Mitigation in PDC Bit Design”, SPE 114673, 2008
34. A. Phillips, D. Gavia, A. Noel, M. Savage, “Adaptive PDC Drill Bit Reduces Stick-Slip and Improves ROP in Midland Basin”, SPE 189706-MS, 2018
35. J.E. Akin, N.R. Dove, S.K. Smith, V.P. Perrin, Chevron “New Nozzle Hydraulics Increase ROP for PDC and Rock Bits”, SPE 37578-MS, 1997
36. F.J. Schluh, A. Coragliotti,C.D. DiCicco, R.A. Nagatani, A. Rea, “Characterization of Encapsulated Oil as an Additive to Water-Based Drilling Fluids: Operational Improvements in Lubricity, Drag and ROP”, SPE 169547-MS, 2014
37. F.B. Growcock, L.A. Sinor, A.R. Reece, J.R. Powers, “Innovative Additives Can Increase the Drilling Rates of Water-Based Muds”, SPE 28708-MS, 1994
38. . Rujhan Mat and Mohd Zulkifi Bin Zakaria, Petronas Carigali, Steve Radford and Darren Eckstrom, Hughes Christensen/Baker Hughes “Innovative Low-Friction

Coating Reduces PDC Balling and Doubles ROP Drilling Shales with WBM" SPE 74514, 2002
39. .https://www.halliburton.com/content/dam/ps/public/bar/contents/Case_Histories/web/DRIL-N-SLIDE-KurdistanIraq.pdf
40. https://www.newpark.com/evolube-g/
41. http://www.alpinemud.com/services_products/alpine_drill_beads.aspx
42. Mojtaba Kalihor Mohammadi and Korush Tamasabi Nowtarki, Pars Drilling Fluids Co.," A Case Study on the Successful Application of Solids Lubricants in Directional and Horizontal Operations to Reduce Torque and Drag and Improve ROP", SPE-176473-MS, 2015
43. Paradigm Runner™ Subs Reduce Torque and Improve ROP, delivering Outstanding Drilling Performance.
44. John E. McCormick, SPE and German Osorio, Weatherford International Ltd, "Adjustable Gauge Stabilizer and Torque and Drag Reduction Tools Reduce Overall Drilling Times ba at Least 20%; A Case study", SPE 141673, 2011
45. Thaiprasert, N., Pensook, T., Tangcharoen, N. and Pattanapong, K, PTTEP. „Drilling Performance Improvement with Rotary Steerable System RSS for Shallow Soft Formation in the Gulf of Thailand ", International Petroleum Technology Conference, 2016
46. Moody, M. and Boonen, P. „Borehole Quality Analysis Comparing Rotary Steerable Tools to Conventional Directional Drilling Assemblies ", PathFinder Energy Services, 2005
47. D. Crane, Y. Zhang, G. Skoff, „Inovative PDC Cutter with Elongated Ridge Combines Shear and Crush Action to Improve PDC Bit Performance", SPE 183984- MS, 2017
48. A.M. Paiaman, M. K. Ghassem, B. Salamani, "Effect of Drilling Fluid Properties on Rate of Penetration" Original Scientific Paper, 2009
49. Bulat. T.: Poslovni rizik i povezanost s revizijom, RRIF, br.1/2007, Zagreb (2007)
50. Srića V.: Menadžment rizika, Veleučilište u Šibeniku, Šibenik (2011)
51. http://www.ef.uns.ac.rs/Download/menadzment_rizikom_master/2009-11-05_teorija_rizika.pdf
52. Narayanan M. P., Nanda V. K., „Financije za strateško odlučivanje", Mate d.o.o., Zagreb (2004)
53. http://www.ztel.fer.unizg.hr/_download/repository/UR11_Tjedan_03_(procjene_rizika,_tehnike).pdf
54. „Smjernice za identificiranje, mjerenje i praćenje rizika kojima je u svojem poslovanju izloženo društvo za osiguranje odnosno društvo za reosiguranje" http://narodne-novine.nn.hr/clanci/sluzbeni/2009_12_155_3859.html
55. Andrijanić I, Gregurek M, Merkaš Z., „Upravljanje poslovnim rizicima", Libertas, Plejada, 2016.
56. https://deseng.ryerson.ca/dokuwiki/design:weighted_decision_matrix
57. https://airfocus.io/blog/weighted-decision-matrix-prioritization/

58. Očevčić, H., „Model procjene vjerojatnosti neželjenih događaja u informacijskom sustavu upotrebom Gayesovog teorema“, Osijek: Sveučilište u Osijeku, 2015

59. https://www.mhnederlof.nl/pos.html

60. https://cran.r-project.org/web/packages/RBesT/vignettes/PoS_codata.html
61. Fabijanić K., Kacian N., Štefan V., „Priručnik stručnjaka za zaštitu na radu I.dio“, IPROZ, Zagreb, 2009
62. Telebec K., Šegović M., Stary D. „Priručnik za izradu procjene opasnosti u malim i srednjim poduzećima prema prilagođenoj SME metodi“, ZIRS, Zagreb, 1997

63. Šegudović, H. „Prednosti i nedostaci metoda za kvalitativnu analizu rizika“, Zagreb: Infigo d.o.o., 2006

64. Crnjac Milić, D., „Mogunost primjene Monte Carlo metode na primjeru agronomskog problema prilikom donošenja odluka u uvjetima rizika“, Ekonomski vjesnik, 2012

65. https://bib.irb.hr/datoteka/859678.Mundjar_Zemljak_-_Value-at-Risk_-_Poucak_-_2016-04.pdf

Nomenclature

BHA Bottom Hole Assembly

HT Handling Tools

KOP Kick off Point

KPI Key Performance Indicator

LOG Logging

LWD Logging While Drilling

NPT Non-Productive Time

MWD Measuring While Drilling

OBM Oil Based Mud

WBM Water Based Mud

PDM Positive Displacement Motor

RPM Revolutions per Minute

RSS Rotary Steerable System

TDS Top Drive System

WBM Water Based Mud

WOB Weight on Bit

WOC Wait of Cement

Appendix A

This appendix describes each of the class and operation codes that are being used in this drilling activities classification system.

Class Codes

◎◎**Planned operations** [PD - Planned Drilling, .PE - Planned Evaluation, PC - Planned Completion]. They are all the operations that have been pre-planned and considered money and time.

◎◎**Trouble operations** [TD - Trouble Drilling, TE - Trouble Evaluation, TC - Trouble Completion]. Include all unplanned operations and all the encountered troubles.

Major Operation Codes

◎◎**BOP - Work with BOP**. Includes all the operation necessary for the preparation, disassemble, recovery and handling of well head and BOP and relevant tests.

◎◎**COMP - Run Completion**. Includes all the operation necessary to run the completion: from the end of operation on production casing with bit /scraper on bottom, to starting of the well testing or rig down.

COR – Coring. Includes all the operation necessary to recover a core: from makeup coring assembly until recovering of last core.

◎◎**CSG - Run and Cement Casing**. Includes all the operations necessary for setting and cementing of casing, liner and tieback. Operations from rig up to run casing until rig down of casing and cementing equipment including waiting on cement.

◎◎**CT - Conditioning Trip**. Includes all the operation necessary for cleaning and conditioning the well for a particular operation [logging, testing, run casing, etc.]. Starting from making until laying down BHA to clean or condition hole prior or between operations. A scraper run during completion is a conditioning trip for completion work.

◎◎**DRLG – Drilling**. Includes all the operations necessary for drilling o the hole: rotating the bit for making hole, circulating, tripping, surveying, reaming, making up BHA, leak−off tests, etc.

◎◎**FISH – Fishing**. Includes all operations necessary to retrieve a fish from the hole or to plug the hole and side track around the fish. The time starts from twisting off the string in the hole, breaking and/or loosing metal in the hole until the hole is ready for commencing drilling at the measured depth reached before the fishing problem occurred.

◎◎**Log – Logging**. Includes all the operation necessary for logging: from rigging up the logging unit to rigging down after last logging run.

◎◎**MILL – Milling**. Includes all the operation necessary for milling material in the hole and milling of casing. From making up until lay down milling assembly including required tripping and circulating for the milling operation.

◎◎**PA - Plug and Abandonment**. Includes all the operation necessary to perform the permanent abandoning of the well from starting of running in hole of the string [DP, wire line &coiled tubing]for the positioning of the first plug [Cement, bridge, etc.], to end of operation on the well

◎◎**RD - Rigging Down**. Includes all the operations for rigging down including all the operations for rig site, anchoring, jacking up/down, ballast and various testing until the rig is released.

◎◎**RM - Rig Move**. Includes all operations required for moving the rig from one location to another.

◎◎**RU - Rigging Up**. Includes all the operations for rigging up including all the operations for rig site, anchoring, jacking up/down, ballast and various testing until drilling operations start

◎◎**STRK - Side Track**. Includes all the operation necessary for preparing the side-track and side tracking from an existing wellbore. Starts from setting cement plug until making hole in formation.

◎◎**SUS - Suspension Operation**. Includes all the operation necessary to perform the temporary abandoning of the well from starting of running in hole [DP, wire line and/or coiled tubing] for the positioning of the first plug [cement bridge, etc.] until the end of operation on the well.

◎◎**TEST - Production Test**. includes all the operation necessary to enable the well to discharge from the rig up of the equipment for well test to rig down.

Operation Codes

◎◎**A – Accident**. Includes Time to lost due any accident.

◎◎**BOP -Work with Blow out Preventers**. Includes all types of work related to BOP, Well Head and riser.

◎◎**CAT - Cased Test /Production Test**. Includes any test performed inside the casing.

◎◎**CIC - Circulate Casing.** Includes circulating when running casing.

◎◎**CIR - Circulate and Condition Mud**. Includes all circulating time while not drilling.

◎◎**CMC –Cement**. Includes starts from rig up to rig down cement head including all line tests

◎◎**CMP -Cement Plugs**. Includes setting all types of cement plugs including P&A.

◎◎**COR –Core**. Includes only time to cut a core using a core bit and barrel.

◎◎**D - Drilling Rotary Ahead**. Includes making hole using rotary assembly driven by top drive or rotary table.

◎◎**DC - Drilling Cement**. Includes drilling Cement Plugs.

◎◎**DFS - Drill Float and Shoe**. Includes drilling float collar and shoe.

◎◎**DHO - Drilling Hole Opening /Undreaming**. Includes opening or under−reaming a pilot hole.

◎◎**DMR -Drilling With Downhole Motor or turbine in Rotary Mode**. Includes rotary drilling with the downhole motor, rotary mode.

◎◎**DMS - Drilling With Downhole Motor or turbine in Sliding Mode**. Includes sliding or non-rotating drilling with DHM in Steering or Sliding mode.

◎◎DO - Drilling Other. Includes drilling other than formation. Does not include drilling cement or cement plugs

◎◎**F– Fishing**. Includes Time required for any fishing operation, includes only working with fish.

◎◎**HT - Handle Tools**. Includes all work related to handling BHA, pick up, make up, break, lay down, rack, all BHA [drilling, coring, milling], test MWD and DHM on surface.

◎◎**LDP - Lay Down Pipe**. Includes laying down/pick up and rack back HWDP/Drill pipe.

◎◎**LOG – Logging**. Includes time for running all types of wire line and while drilling logs (LWD). Time starts from rigging up wire line logging unit till rig down.

◎◎**LOT - Leak Off Test**. Includes normal time to conduct Leak Off Test LOT or Formation Integrity Test FIT. It may include other operation [e. g. Circulation or drill formation] if logged as one event with the Leak Off test.

◎◎**M – Milling**. Includes any milling operation (windows, junk, casing) even if measured depth does not change.

◎◎**O- Other**. Includes time for unlisted operation activity.

◎◎**OHT - Open Hole Tests**. Includes all open hole tests starts from make-up and trip in with test assembly till it pulled out after finishing test.

◎◎**POR - Pulling Out Riser**. Includes Time actually spent to retrieve all riser pipe

POV - Position Offshore Vessel. Includes positioning rig to be in drilling position.

◎◎**RC - Run Casing**. Includes Normal time to rig up, run casing/tubing and rig down casing/tubing equipment.

◎◎**RD - Rig Down**. Includes only rig down the rig.

◎◎**RDR – Run Down Riser**. Includes Run down the riser for offshore operations.

◎◎**RO - Repair Other**. Includes all repair and routine service for other than rig's equipment.

◎◎**RR - Rig Repair/Service**. Includes all repair and routine service for rig's equipment.

◎◎**RU - Rig up**. Includes only rig up the rig.

◎◎**RW - Ream & Wash**. Includes pick up kelly, circulate and rotate the string through tied spots while polling out or running in hole.

◎◎**S – Survey**. Includes normal time consumed to survey a well while not drilling and obtain a valid result.

◎◎**SA – Subsea Activities**. Includes All work related to subsea equipment.

◎◎**ST – Short Trip**. Includes any trip, which is not a reamed trip and does not go from top to bottom or bottom to top of borehole.

◎◎**TI - Trip In**. Includes tripping in hole from surface to TD.

◎◎**TO -Trip Out**. Includes tripping out of hole from TD to surface.

◎◎**WC - Well Control**. Includes all operation involved to control pressures inside the well.

◎◎**WO - Wait On**. Includes time for operation suspended due to waiting for anything till operation resumes as planned.

◎◎**WOC - Wait On Cement**. Includes Waiting on cement to harden enough to resume next activity.

Trouble Type Codes

◎◎**BB - Bit/BHA Balling**. Includes lost time due to Bit/BHA Balling.

◎◎**BP – Bit Problems**. Includes lost time due to any problem relating to bits.

◎◎**BHA - BHA Failure**. Includes lost time due to BHA failure [down hole motor, jar, stabilizer, basically any BHA component other than surveying or logging tools].

◎◎**BHS - Bore Hole Stability**. Includes lost time due to Well Bore Instability.

◎◎**BOP - BOP/Well Head**. Includes lost time due to problems during BOP/well head operations.

◎◎**CMT – Cementing**. Includes lost time while cementing [bad cement job].

◎◎**DD - Directional Drilling**. Includes lost time due to directional drilling problem [directional control and trajectory].

◎◎**DRG – Drag. Includes problems with drag**. This code might be used as a problem indicator rather than lost time code.

◎◎**DS - Drill String**. Includes lost time due to drill string failure [pipe wash out].

◎◎**FISH– Fish**. Includes lost time due to fish in hole.

◎◎**HC - Hole Cleaning**. Includes lost time due to hole cleaning problem.

◎◎**JF - Job Failure**. Includes lost time due to Job Failure. I a job [test, completion] was run unsuccessfully NOT due to tools malfunction or damage or a hole problem.

◎◎**LOC - Loss of Circulation**. Includes lost time due to loss of circulation.

◎◎**MUD – Mud**. Includes lost time due to mud/hydraulic parameter.

◎◎**NT - No Trouble**. Includes no trouble. This is a compulsory field and must be filled in the case of no trouble.

◎◎**O– Other**. Includes lost time due to unlisted problems.

◎◎**RO - Repair Other**. Includes lost time due to repairing service company's equipment.

◎◎**ROP - Rate of Penetration**. Includes lost time due to low ROP [due to choosing wrong bit for formation, normally changing bit after only a few hours of drilling with new bit].

◎◎**RR - Rig Repair**. Includes lost time due to rig repair.

◎◎**S– Survey**. Includes lost time due to surveying [mis−run].

◎◎**STK – Stuck**. Includes lost time due to pipe stuck.

◎◎**TF - Tool Failure**. Includes lost time due to tool failure [downhole or surface], mainly service company tools, not used for BHA components other than logging and survey tools).

◎◎**TH - Tight Hole**. Includes lost time due to tight hole.

◎◎**TRQ – Torque**. Includes lost time due to excessive torque.

◎◎**WC - Well Control**. Includes lost time due to well control operation.

◎◎**WO - Wait On**. Includes lost time due to well control operation.

◎◎**WOW - Wait on Weather**. Includes lost time due to waiting on environmental conditions [weather or daylight].

Appendix B

Software Available in the Market

While using probabilistic estimation and/or Monte Carlo simulation, a number of software can be used as a tool. Software selection differs with users and organizations. Some companies have established their own software or spreadsheet for drilling cost estimating purpose. Some organizations operate available commercial software for their forecast. Frequently, the commercial software used in cost valuation activity is a spreadsheet-based application which allows users to perform Monte Carlo simulation from their present spreadsheet software. Major oil field service companies also offer well cost valuation and risk analysis software as one of their services. In this case, the software providers generally propose other services and/or software which have the potential to enhance the competence of cost estimation.

Model Risk Software

Model Risk is a spreadsheet-based application which is right for prognostic modelling, forecasting, simulation and optimization. It uses Monte Carlo simulation to estimate and record the results of thousands of diverse scenarios. Analysis of these cases exposes the range of possible outcome, their likelihood to occur, the input that most impact the model and the key point that should be focused on.

RiskAnalysis with Model Risk

You can complete a risk analysis in some ways, but one method includes building a spreadsheet model. A good spreadsheet model can be actual helpful in identifying where your risk might be, since cells with formulas and cell references classify causal relationships among variables. One of the disadvantages of conventional spreadsheet models, however, is that you can only enter one value in a cell at a time. A spreadsheet will not let you to enter a range or multiple values for a cell, only one value at a time. So, calculating the range needs you to replace the uncertain value several times to see what effect the minimum, most likely, and maximum values have. Calculating more realistic "what-if" scenarios is the same, except it requires you to transform your spreadsheet even more.

Model Risk helps you outline those uncertain variables in a whole new way: by defining the cell with a range or a set of values. So, you can define your price range let say for an example between 3000$ and 5000$, instead of a using single point estimate of 3200$. This principle can be used for any time we have some uncertainty in our forecast. It then uses the clear range in a simulation. In addition, Model Risk preserves track of the results of each scenario for you.

Uncertain Variables in Spreadsheet

For each uncertain variable (one that has a choice of possible values), you state the possible values with a probability distribution. The type of distribution you select is based on the conditions surrounding that variable. Distribution types include:

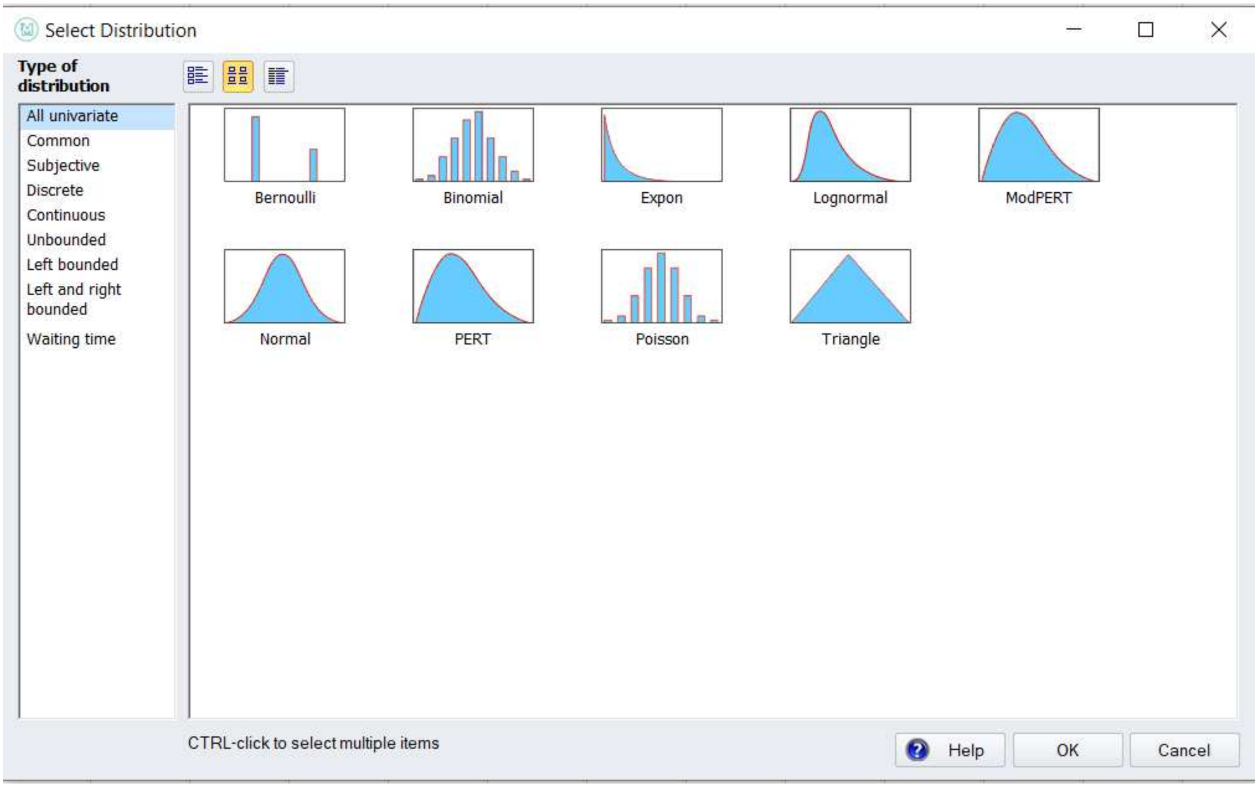


Figure 42: Uncertain Variables in Spreadsheet

To add this sort of function to an Excel spreadsheet, it would be desirable to know distribution characterization. With Model Risk, these equations are automatically designed. Model Risk can even fit a distribution to any historical data that you might have. In this case triangular distribution type will be used

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