FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study program/specialization: Computational Engineering	**Spring semester, 2021** Open
Author: John Magne Langelandsvik	john magne (Author's signature)

University Supervisor: Aksel Hiorth, University of Stavanger

External Supervisors: Morten Laget & Øystein Texamo Prytz, Well Expertise AS

Title of master's thesis:

Probabilistic Time Estimation for Drilling Operations on NCS Using Monte Carlo

Tittel på masteroppgave:

Sannsynlighetsbasert Tidsestimering for Boreoperasjoner på NCS ved bruk av Monte Carlo

Credits (ECTS): 30

Keywords: Probabilistic Monte Carlo Drilling Oil & Gas Time Estimate Decision Making Modelling & Simulation Digitalization Risk Value Erosion	Number of pages: 67 Supplemental material/other: + 2 Stavanger, 06/07/2021

Acknowledgements

First and foremost, I would like to start thanking my employer, Well Expertise AS, for many years of incredible follow-up prior to starting on my master thesis, resulting in this very specific and scientific work that will help decision makers in the industry of oil and gas to further increase their value generation. This thesis proposal I received from Well Expertise has guided me further into the research field. A big thank you to Morten Laget and the boys.

It would not have been possible to write and show the results of the work done without help from Wellesley Petroleum AS, where they have been helpful with data and their approval to use the data publicly in this thesis.

Furthermore, the work could not have been done without the very new specialization field computational engineering at the University of Stavanger. My year of study is the rudimentary group that is writing a master's thesis in the field and let us be the guinea pigs and set the standard for future engineers.

A thank you to my university supervisor, Aksel Hiorth, giving me the freedom to write this thesis and make my own timeline. Working full-time as a drilling engineer in combination with finishing this master's program and thesis in ordinary time has made the time management difficult but manageable due to the freedom given by my supervisor.

Abstract

The purpose of this thesis is to present a probabilistic methodology for developing time estimates for drilling operations on the NCS, which can further be expanded to supplementary continental shelfs in the world, or for more specific drilling areas within a continental shelf. The Monte Carlo-model take advantage of the real historical data, where the P90-, P50- and P10 percentiles are derived and used in the probabilistic model. Utilizing risk analysis in the model makes the probabilistic methodology strong and not biased.

By taking advantage of historical data together with analytics and providing the dataset into the Monte Carlo model, it is simulated probabilistic ranges expected for one specific well. Historical data are often stored and forgotten in every company and not exploited to further increase the decision making and result. By leveraging historical data and make data-driven decision making it will ultimately generate more value in the long term.

By comparing the presented Monte Carlo model with a traditional deterministic and a 3rd party probabilistic model, the results show promising outcome based on two compared drilled wells. Together with additional and richer data, the proposed Monte Carlo model leveraging historical data will increase its robustness and deliver better decision making foundation for the future opposed to the biased and heuristic methods used today.

Nomenclature

Abbreviations

AFE	Application for Expenditures
BHA	Bottom Hole Assembly
CLT	Central Limit Theorem
DDR	Daily Drilling Report
EZSV	External Zentralized Safety Valve
E&P	Exploration & Production
FIT	Formation Integrity Test
KPI	Key Performance Indicator
LOT	Leak-Off Test
MC	Monte Carlo
MD	Measured Depth
NPT	Non-Productive Time
POOH	Pull Out of Hole
PP&A	Permanent Plug & Abandonment
P&A	Plug & Abandonment
RIH	Run in Hole
ROP	Rate of Penetration
TD	True Depth
TF	Trouble Free
TOC	Top of Cement
TVD	True Vertical Depth
WOW	Waiting on Weather

Mathematical Abbreviations

δ_{error}	Percentage error
ν_A	Actual drilling time
ν_E	Expected drilling time
knots	Nautical Miles per Hour
m/hr	Meters per Hour
std/hr	Stand of Pipe per Hour

Monte Carlo Abbreviations

Mean	Average of the dataset
P10	10th Percentile
P50	50th Percentile
P90	90th Percentile

Table of Contents

PART I

LITTERATURE STUDY AND MONTE CARLO MODELLING IN THE OIL AND GAS INDUSTRY

1. Introduction

1.1. Background

Drilling of an oil and/or gas well is done in several phases until the target is reached. Firstly, by using a relatively big drill bit to penetrate the subsurface until a certain depth, followed by casing off the drilled section using a type of steel tube. The steel tube is then cemented in place before a smaller diameter drill bit is used to commence drilling deeper into the subsurface. A well is drilled into the target normally in four to six phases.

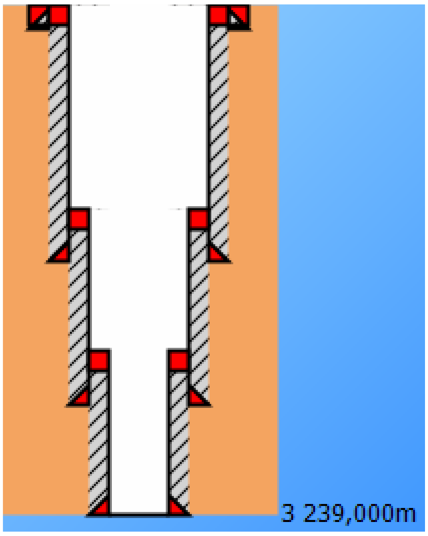


Figure 1: An example well sketch for an offshore well with different sections. (Løberg et al. 2008)

It is estimated that 70 to 80% of the total cost of an oil or gas well originates from the time it takes to drill the well (Coelho D. K. et al. 2005, p. 1892). An exploration well can take one year from start of planning to end of operations. The operational time used to drill the well normally ranges between 30 to 60 days, which equals 8.2 to 16.4 percentage of the time. The high cost associated with the drilling operations is due to high daily cost for an offshore drilling rig, which can either be a semi-submersible rig, jack-up or a drill ship. Hence, it is essential to make accurate time estimates of the drilling operation in order to make accurate Authorization for Expenditure, AFE.

When an operator provides funds to drill one exploration well, the optimal scenario is to allocate just enough, not more or less, to drill that specific well (Peterson S. K. et al. 1995, p. 305). Providing just enough funds for a project will allow more promising prospects to be drilled, opposite to over-budgeting and having unused funds left over that does not generate any return on investment. A combination of risk analysis together with big datasets yields higher accuracy and a probabilistic range describing what can be expected and will lead to better superintendency of the financial uncertainty and risk for the cost impact of the drilling operations (Mireault R. 2013, p. 14).

Risk-based studies using Monte Carlo simulations have been used broadly in the field of petroleum in the past three decades and numerous different problem areas have been researched on since then (Peterson S. K. et al. 1995, pp. 305-307). For instance, Marathon Oil published papers addressing Authorization for Expenditure (AFE) estimates using Monte Carlo as early as the 90's and investigated methods to generate AFE models for development projects using a high-level method for estimating the days used drilling. Monte Carlo simulations have also been used on production forecasting (Murtha J. 2006), corrosion inspection (Hurd C. et al. 2018), casing design (Muoghalu A. et al. 2020), estimation of in-situ stresses (AlTammar M. and Alruwaili K. M. 2020) and other areas within the petroleum sector. A significant number of papers and research have been made and done from the mid 90's to today, where the methods in the last decade have become sophisticated and accurate. The work done by Mohus (2018) substantiate the improvement in the decision making where the average cost overrun decrease from the 90's to 2018.

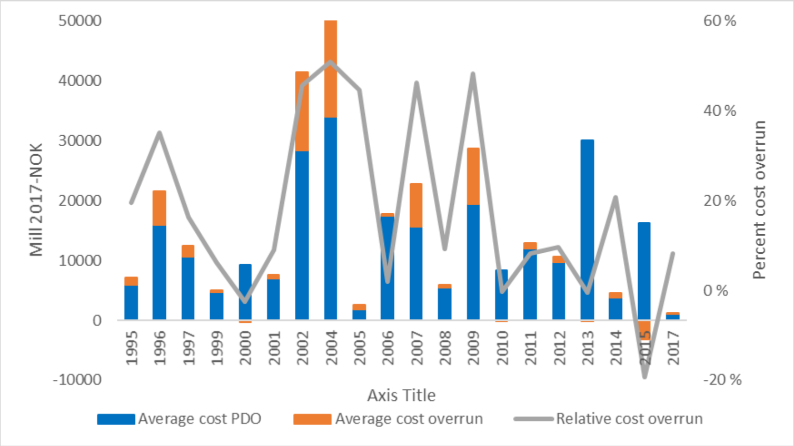


Figure 2: Average cost, average cost overrun, and relative cost overrun for fields on the NCS. Sorted by year of PDO approval. (Mohus 2018)

The next sub-sections describe the problem in more detail and how it is solved using probabilistic methods to make a better decision basis.

1.2. Problem Description

A drilling time estimate consist of several phases with a degree of uncertainty and associated risk factors (Coelho D. K. et al. 2005, p. 1892). Especially, for exploration wells drilled in more uncertain areas with less geological knowledge the uncertainty increases with regards to the drilling parameters and uncertain events such as a stuck pipe, broken bit, kick, shallow water or gas flow. Drilling of the top-hole sections are for example phases that contains uncertainty. A single E&P-company may drill several top-hole sections a year and will collect the real-time data used during operations for every well and will after years of drilling exploration, appraisal and development wells possess a suite of data for each specific phase and sub-phase.

A study performed by AGR Software in 2016 says that ‘’…a lot of effort is spent on gathering, cleaning and normalizing the data over and over, leaving less time actually analysing data and planning operations’’. One of the findings in the study pinpoints the difficultness, lack of expertise and knowledge of the value generation associated in such amount of data (Snøtun H. 2016, p. 2). Using the data is not about miniaturizing risk but rather about adding value and quantifying the uncertainty. It is therefore essential to use the available data in a favourable manner.

In today’s technological world, the way of thinking should be built on data-driven analysis based on prior experiences and learnings to influence the decision-making process, and not a deterministic approach (Snøtun H. 2016, pp. 1-2). Every drilling company got data on the timings for each operation done offshore and may store them somewhere. To capitalize on the stored datasets, which can be a significant amount of data, may be a challenge and should be the focus of every organization. A MIT study shows the top-performing companies use analytics twice as much as their peers, succeeding using analytics in both big and smaller areas (Lavalle S. et al. 2011, p. 21).

1.3. Objectives of Research

In this thesis, a Monte Carlo simulation model will be used to estimate the uncertainty in drilling operations. The Monte Carlo model is based on historical drilling data where three percentiles are extracted and used in the Monte Carlo simulations to yield better data driven estimates and decisions.

For each drilled well, the timings used for phases and sub-phases will be accumulated in an Excel-sheet and/or daily drilling reports (DDRs). These data are unfiltered with a total time, which includes timings that are not solely operational progress but may include stop in the operation or maintenance. To get informative data out of the operational reports one must filter it properly and use the raw data in probabilistic models. One of the reasons why companies are not advancing from available data is due to lack of knowledge on how to handle the dataset correctly and find ways to gain value from it.

The decisive objective of this research is to use the model further in the company to benefit on available data to increased customer satisfaction and competitiveness of the company by leveraging data and make better decisions.

2. Literature Study

2.1. Monte Carlo Preface

Where do the Monte Carlo calculation method derive from? A group of scientists worked on the maturation of nuclear weapons in the beginning of the second world war in the 1940s, which applied the essence of gambling; specifically, the behaviour of outcome and probability, i.e., games of chance (Kalos M. H. and Whitlock P. A. 2008, p. 1). The Monte Carlo method is based on probabilistic and numerical interpretations rather than computers, but effectiveness of the simulations requires modern computational power.

One example of a Monte Carlo calculation and simulation is the chance of winning in a solitaire (Kalos M. H. and Whitlock P. A. 2008, p. 2). It lays one fundamental statistical assumption that the card deck is completely random. One player with a specific skill level has one strategy of playing the game from start to finish. The player will randomly reshuffle the deck after either winning or losing the game several times after each other that will lead to a better set of data in the Monte Carlo model. The result is a Monte Carlo estimate that contains the chance of success for winning Solitaire for that particular player, and with more data, the accuracy of the Monte Carlo model increase.

The work presented by Mohus (2018) describes the overruns both in cost, schedule and production volumes and rates. Mohus states that the overrun in estimated development costs is up to 25 percent for the 68 fields data were collected from. One of the causes found for over-estimating over and over again was biases, and it is the data that is put into simulations that are biased (Mohus E. 2018, p. III).

One way to address the problem of biases is the use of historical and offset data. Preferable, in an area where good offset data is available, one should try to incorporate the offset learnings and use real historical drilling data where applicable in order to make deterministic estimates and a more developed view of the well cost, in other words the Application for Expenditure (Peterson S. K. et al. 1993, p. 2).

2.1.1. Monte Carlo Percentiles

The most common used mathematical terms in Monte Carlo literature are the P90-, P50-, P10- and mean percentiles. They do represent different confident intervals and are often misunderstood as percentages. A summary of what they represent are given below.

- P90-percentile: 90 out of 100 outcomes will be above this estimate.
- P50-percentile: The middle, or median, estimate, where 50 out of 100 outcomes will be above, and 50 outcomes below this estimate.
- P10-percentile: 90 out of 100 outcomes will be below this estimate.
- Mean: The average of all values.

Due to the mean value being the average of all simulated values, it will often represent a percentile between the P40 and P30 value. A common denominator in the petroleum industry is that the middle estimate yields a value closer to the P90-percentile relatively to the P10-percentile, as pointed out in the illustration beneath.

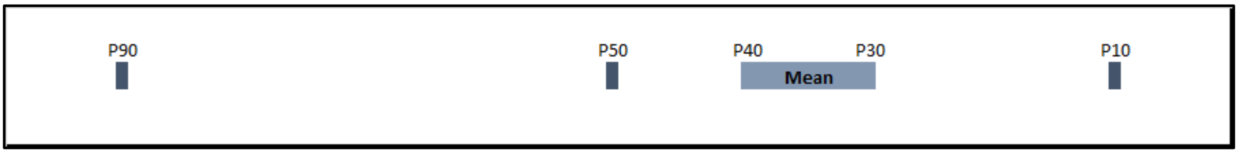


Figure 3: Illustration of the common percentile's relativeness.

Especially for estimates involving time, the mean value deflects towards the high-estimates, P40 and P30. It is therefore chosen to use the P50 percentile for further analysis in this thesis.

2.1.2. Random Walk

Random walk theory has been widely known due to its diverse applications using probability in science, engineering, modelling spread of diseases and beyond (Kalos M. H. and Whitlock P. A. 2008, p. 107). A random walk is a set of random variables, as described in chapter 2.1, of $X_0, X_1, X_2, \dots, X_n$ and is representing a system for a "time" n being $n = 1, 2, \dots, N$. There is a probability going from state i at a time n over to state j at the time $n + 1$ expressed as,

$$P_g = P[X_{n+1} = j \,|X_n = 1] \tag{1}$$

and will in all circumstances be independent to prior to state i. Such processes are called Markov Chain, or stationary probability processes. Random walk can be described by an intoxicated human being randomly taking a step in either four directions: north, south, west or east, if the choice only exist of the four.

2.1.3. Central Limit Theorem

In Markov Chain Monte Carlo (MCMC), also called a 'random walk', the presence of a central limit theorem (CLT) is an essential practical problem (Probability Surveys 2004, pp. 300-305). A general characterization of the central limit theorem can be defined as,

$$S_n = \sum_{i=1}^{n} Y_i \tag{2}$$

$$\sigma_n^2 = ES_n^n \tag{3}$$

According to the central limit theorem, the calculated average of a random independent variable will be distributed into a normal distribution (Hiorth A. 2021, p. 130). This theorem only holds for any data sample if the sample size is large enough, usually with over 30 data points. It is also worth to mention that the theorem only holds for independent variables, meaning variables that interact will not have the same distribution. Practically, this theorem has been used in oil reserve estimations, whereas corporate reserves can be estimated by summarizing the single well reserves (Kerr R. 1997, pp. 98-101). The uncertainty of the corporate reserve estimation would then be expected to obtain a normal shape distribution according to the central limit theorem. Monte Carlo modelling can then be applied, such as the MCMC model, to further reduce the uncertainty level.

2.1.4. Markov Chain Monte Carlo Method

For any initial state of a MCMC with constant distribution is exclusive if it has a probability higher than zero of using any distribution room which is another possible state (Kalos M. H. and Whitlock P. A. 2008, p. 108).

$$\sum\nolimits_{j=1}^{N} P_{ij} = 1, \qquad i = 1, 2, \ldots, N \tag{4}$$

Where state j is accessible if it can be reached from state i for a finite integer of steps, and if state i can be reached from state j, the states are defined as communicators. In the instance where they do not communicate, then $P_{ij} = 0$ or $P_{ji} = 0$. A Markov Chain Monte Carlo where all states communicate with each other is called irreducible.

Assume a random discrete variable with a function of probability mass noted as $p_j = P\,\{X = j\}$, where $j = 1, 2, \ldots, N$ (Kalos M. H. and Whitlock P. A. 2008, pp. 109-110). If an irreducible aperiodic Markov Chain is created, one can sample the room such $p_j = \pi_j$ in the room $j = 1, 2, \dots, N$, to extract values of X_n when n is of big enough. The estimator for one character, $h(X)$, of a system described as $E\big(h(X)\big) = \sum_{j=1}^{N} h(j) p_j$ be equal to the different states one reaches in a random walk, equal to:

$$E\big(h(X)\big) \approx \frac{1}{m} \sum_{i=1}^{m} h(X_i) \tag{5}$$

One important note in a Markov Chain is that the next state, $n + 1$, is dependent on how the previous state, n, behaves. It therefore requires several simulations to obtain results that is not influencing the distribution due to the dependency of the previous state. In order to offset such behaviour to be valid in the model, one adds a constant k making the equation valid k-states from i,

$$E\big(h(X)\big) \approx \frac{1}{m - k} \sum_{i=k+1}^{m} h(X_i) \tag{6}$$

Where the constant k is govern by the properties of the function and may be as low as zero or higher than a thousand.

2.1.5. Triangular Distribution

The triangular distribution is used in the simulations due to a limited amount of offset drilling data. In a triangular distribution there is three parameters: upper limit b, mode m and lower limit a, as shown in Figure 4 (Stein W. E. and Keblis M. F. 2008, pp. 1144-1145).

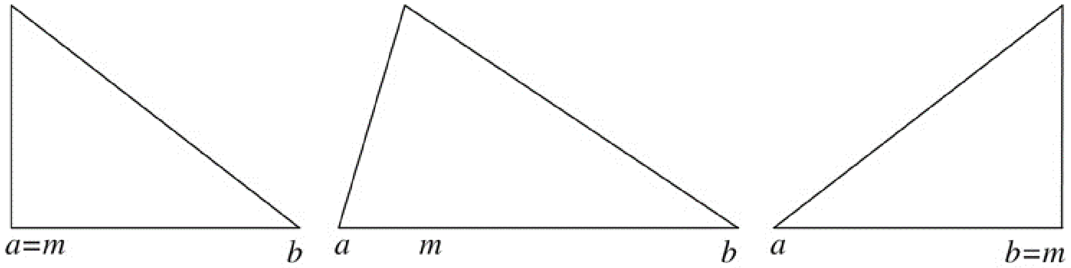


Figure 4: The Three Different Triangular Densities. Left and Right Figures Represents Minimum and Maximum of Two Uniform Variates. A Typical Triangular Density is Shown in Middle, with Mode m (Stein W. E. and Keblis M. F. 2008)

Height of the triangle is determined by the spread of parameters going into the distribution, and the area in each triangle need to be 1 unit. In the cases shown in Figure 4, one can denote the left and right triangle as a left-triangular and right-triangular density, while the mid triangle is a symmetric triangular if $m = (a + b)/2$, i.e., symmetric around m.

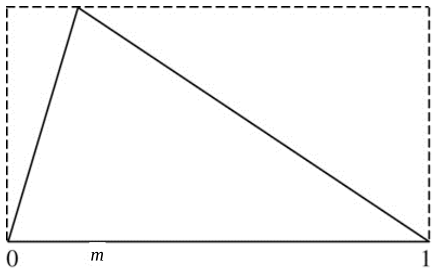


Figure 5: Triangular Density with a Mode c in (0,1). The Dashed Lines Representing a Rectangle is the Region Between the Triangular Density and Horizontal Axis as a Subset (Stein W. E. and Keblis M. F. 2008)

Triangular distributions are frequently used in applications containing big datasets, therefore an emphasis on the efficiency to simulate it is a focus point (Stein W. E. and Keblis M. F. 2008, pp. 1143-1144). During simulation of random variables, a significance upon factors like speed, range of applicability, set-up time, machine independence, length of compiled code and simplicity and readability are important when deciding distribution method. For cumulative non-uniform distributions, the inversion method, $F^{-1}(u)$, $u \in [0,1]$, is the general and most used method for simulation of triangular distributions. Below, the inversion method is shown (Stein W. E. and Keblis M. F. 2008, p. 1144).

$$f(x) = \begin{matrix} 2x/c, & if\ 0 \leq x \leq c \\ 2(1-x)/(1-c), & if\ c \leq x \leq 1 \end{matrix} \tag{7}$$

$$F(z) = \begin{matrix} z^2/c, & if\ 0 \leq z \leq c \\ 1-(1-z)^2/(1-c), & if\ c \leq z \leq 1 \end{matrix} \tag{8}$$

Generalized to,

$$F^{-1}(u) = \begin{matrix} \sqrt{cu}, & if\ 0 \leq u \leq c \\ 1-\sqrt{(1-c)(1-u)}, & if\ c \leq u \leq 1 \end{matrix} \tag{9}$$

2.1.6. Chosen Monte Carlo Setup

The chosen Markov Chain Monte Carlo utilizes the triangular distribution together with the three percentiles, P90, P50 and P10, as the base for the simulations. In the MCMC-method presented in this thesis, there is used 50,000 simulation steps. This is done to achieve a sufficient result that is not dependent on the previous step, as described in sub-chapter 2.1.4. Markov Chain Monte Carlo Method.

2.2. How to Make Good Decisions

A great quantity of this thesis work circulates around making the best possible decision based on reliable data. To make good decisions is not always simple, where decision making theory focuses on bias, heuristic, and probabilistic way of thinking.

Heuristics and biases are cognitive mechanisms, a set of decision rules as well as subjective judgments used in decision making (Busenitz L. W. and Barney J. B. 1997, pp. 12-13). The use of cognitive mechanisms is highly popular due to its simplicity, and it is less time consuming compared to probabilistic methods, giving the decision makers an easy tool to make acceptable solutions to sophisticated problems. The terms heuristic and bias addresses individuals simplified strategy to make decisions in complex and uncertain circumstances.

‘’Change the decision-making process and cultural change will follow’’ said Vince Barabba (1995). In order to make high-quality decisions the methodology has to include one decision making tool that yields value and a clear probabilistic range of values (Bratvold R. B. and Begg S. H. 2010, p. 17). Real-world decision problems are complicated and tends to be poorly described using deterministic methods. The deterministic methods are based on intuition or instinct, i.e., biases, and have been popular in the E&P-industry because of how quick and easy it is in addition to it requiring less analysis. This can in some cases be efficient and accurate but will in larger areas with more uncertainty coupled with a high economical cost be a real jeopardy. Because of the high economic impact associated with the uncertainty range, using a proper decision-making tool is crucial in most industries.

As engineers, it is important to update the probabilities along with new information from recently drilled wells (Bratvold R. B. and Begg S. H. 2010, pp. 132-133). A probabilistic estimate is the belief of something historical is going to repeat itself in the future. To make better estimates of something happening in the future, it is necessary to update the model with more and recent data along the way resulting in a more realistic estimate to base the decisions on.

2.2.1. Decision Elements

First step of decision making is to identify the main elements in the problem, as summarized below (Bratvold R. B. and Begg S. H. 2010, pp. 21-22).

1. Alternatives in the decision problem.
2. Preferences and objectives that is the focus for the decision maker.

3. Information and data about the uncertain event.
4. Net present value, or outcome, for each individual alternative.
5. Decision, the conclusive choice between the alternatives.

First three of the elements mentioned above is the so-called ‘decision basis’ (Bratvold R. B. and Begg S. H. 2010, pp. 21-22). A figure showing the relationship of all five elements are shown below, yielding the foundation for all decision problems. In general, the information one receives together with a set of alternatives and objectives generates a forecasted payoff, which may be of uncertain character, to establish the decision on. Every rational decision maker would choose the alternative maximising the payoff.

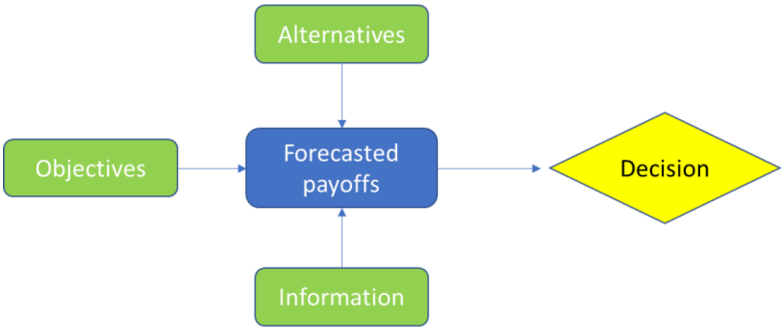


Figure 6: Elements in Decision Making (based on Bratvold and Begg 2010).

2.2.2. The Three Phases of Decision Making

A decision-making methodology are developed after defining the five decision elements, as described above (Bratvold R. B. and Begg S. H. 2010, p. 28). Good decisions are characterized as ‘an action we take that is logically consistent with our objectives and preferences, the alternatives we perceive, and the information we have’, according to Bratvold and Begg (2010). The following methodology consist of three phases with a set of steps in each phase to make sure a high-quality decision is made.

Before moving to the details in the three phases of decision making, one must acknowledge that the presented model is adaptable to the size and significant of the decision (Bratvold R. B. and Begg S. H. 2010, p. 29). Decisions that are regarded as low impact for the company does not require all the steps but rather the rational way of thinking. That meaning, out from the three phases and set of steps, one should learn to adapt the structured thinking and how an objective should be thought of. For larger decisions for companies, the decision model should include numeric calculations and analytical procedures.

- Phase 1 – Structuring (Framing):
    1. Define the decision context (decision, decision maker, and feasibility).
    2. Establish the objectives (criteria) such each alternative can be evaluated with regards to that.
    3. Create the different alternatives to choose between.

- Phase 2 – Modelling (Evaluating):
    4. Calculate the expected value, or payoff, of each individual alternative with regards to the objectives.
    5. Weigh the objectives relative importance with regards to their respective probabilities to distinguish among the alternatives.
    6. Calculate and decide the overall best performing alternative for the overall probability before choosing the relatively best performing one.

- Phase 3 – Assessing and Deciding:
    7. Evaluate trade-offs between the contrasting alternatives.
    8. Execute a sensitivity analysis of each probability and known information, as they are all uncertain. This will test how robust the outcome and decision are.

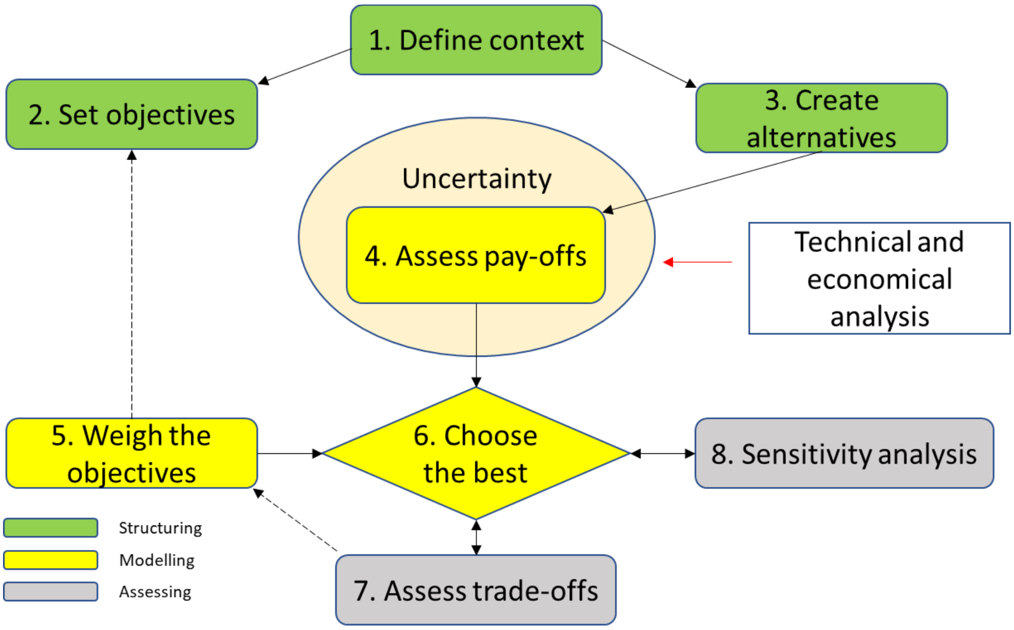


Figure 7: Diagram of the decision-making methodology (based on Bratvold and Begg 2010).

2.3. Traditional Time Estimation

Traditionally, time estimates for the drilling operations have been constructed using deterministic values (Løberg T. et al. 2008, pp. 2-3). Timings are in several cases based on a single value giving the most likely time it takes to drill the well and may sometimes comprehend a low and/or high case also, often incorrectly used as the P90- and P10-percentile. The traditional deterministic way does not provide a legitimate uncertainty picture and yields a high mean associated with a low uncertainty.

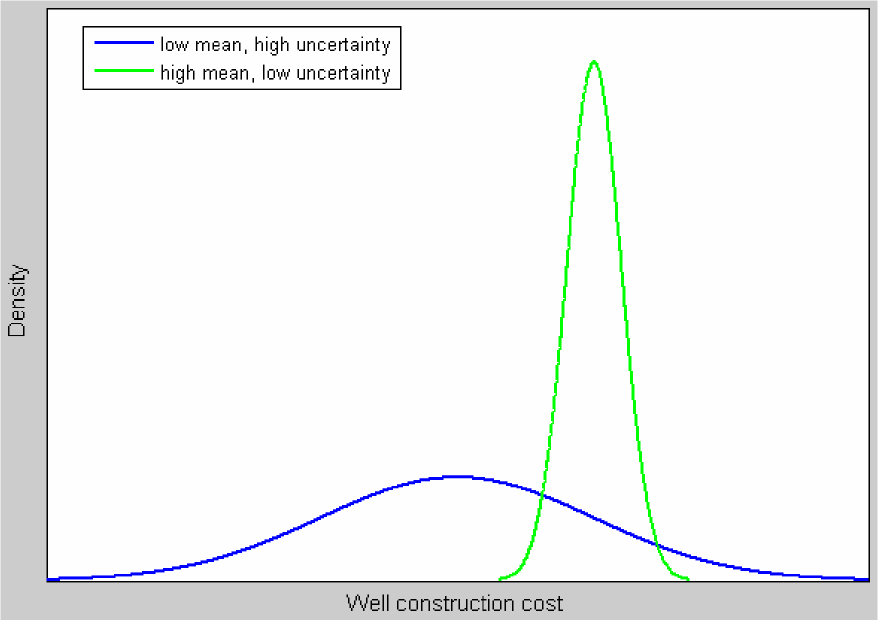
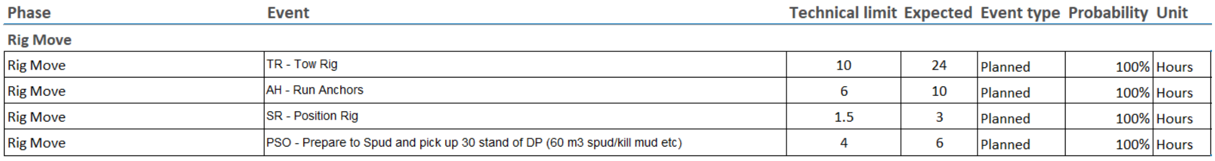


Figure 8: Comparison of two methods to estimate well cost uncertainty (Løberg et al. 2008)

Estimates of the timings are based on cognitive experiences from the past and the personal biases is the governing benchmark (Caso C. 2020, pp. 5-6). With the use of big Excel-spreadsheets together with macros and legacy software programs, the drilling engineer input their cognitive experiences to estimate the timings for their specific well project. Let us say the engineer delivers a P50 estimate of a total of 45 days to the upper management and the project gets approved based on the relative low cost. Mid-way in the project, a new engineer overtakes and updates the time estimate based on his or her biases, resulting in an estimate of 49 days, further communicated to the upper management. Total cost of the project just increased and due to limited funding from the company, they must drop a promising project in the portfolio. The result from personal biases as the standard erode value, as described in Chapter 1.



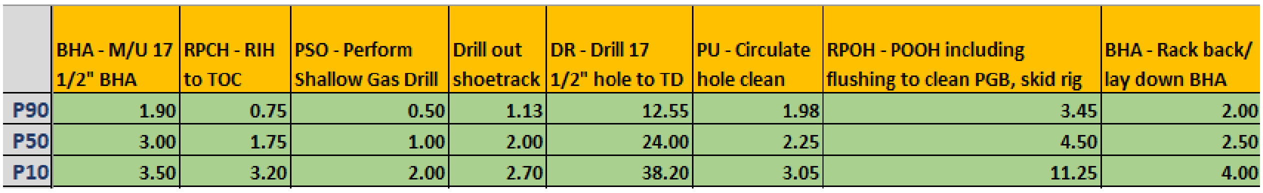
Phase	Event	Technical limit	Expected	Event type	Probability	Unit
Rig Move						
Rig Move	TR - Tow Rig	10	24	Planned	100%	Hours
Rig Move	AH - Run Anchors	6	10	Planned	100%	Hours
Rig Move	SR - Position Rig	1.5	3	Planned	100%	Hours
Rig Move	PSO - Prepare to Spud and pick up 30 stand of DP (60 m3 spud/kill mud etc)	4	6	Planned	100%	Hours

Figure 9: Example of a deterministic and bias time estimate.

2.4. Probabilistic Time Estimation

Using a probabilistic method in combination with data to build an estimate of drilling timings yields a realistic variation that reflects the uncertainty related to the operations (Løberg T. et al. 2008, pp. 2-3). To employ historical data as the foundation of a time estimate gives quicker predictions with no human errors. As the foundation of the time estimate is solid, the engineers may go in and add and edit both phases and sub-phases to adjust the risk picture exemplify offset experiences and learnings. An efficient foundation based on a probabilistic method will conclusively enhance the decision making and process.

One thing to commemorate is the existence of a handful contrasting probabilistic methods in today's mathematics. When evaluating prospects or problems containing a degree of uncertainty, the use of Monte Carlo simulations has been acknowledged by engineers and other professionals because of how such simulations treat the data points, described in detail in chapter 2.1.



	BHA - M/U 17 1/2" BHA	RPCH - RIH to TOC	PSO - Perform Shallow Gas Drill	Drill out shoetrack	DR - Drill 17 1/2" hole to TD	PU - Circulate hole clean	RPOH - POOH including flushing to clean PGB, skid rig	BHA - Rack back/ lay down BHA
P90	1.90	0.75	0.50	1.13	12.55	1.98	3.45	2.00
P50	3.00	1.75	1.00	2.00	24.00	2.25	4.50	2.50
P10	3.50	3.20	2.00	2.70	38.20	3.05	11.25	4.00

Figure 10: Example of Monte Carlo Percentiles form the dataset.

2.5. Workflow for Probabilistic Time Estimation

After a well is drilled, whether it is an exploration, appraisal, or production well, one has to save all the raw data in a database with the timings used for each phase and sub-phase. Different operators may divide phases and sub-phases variously, therefore, the presented phases and sub-phases is not the solution for everyone, and it can also be further divided into micro KPI's (Key Performance Indicator). The available data from the company have the same ruleset for all wells, making it convenient to keep this structure in the model.

Anomalies in the raw dataset must be filtered away before used in a probabilistic model. Waiting on Weather and Non-Productive Time, hereby denoted as WOW and NPT, are two anomalies that has to be removed from the raw dataset. In every Daily Drilling Report, DDR, it is specified how many hours of WOW and NPT there is, if any. Upon completion of removing WOW and NPT, the dataset is no longer raw and is ready to be used in the model.

In this thesis, raw data from all wells drilled within the company have been found, filtered, and normalized. The raw data are filtered and normalized in a general Excel-file followed by using Python to make databases based on the respective phases and sub-phases. Databases in Python are easy to maintain and is directly linked to the Excel-file.

2.6. Downtime in Drilling Operations

A study by Adams et al. (2009) shows that downtime, in other words WOW and NPT, are discrete statistical events depending on the time of year the well is drilled, which type of drilling rig used, and well operation limitations. The two downtime events can further be categorized as extreme and parent NPT, and open water and riser connected WOW. In their paper they conclude that the uncertainty in NPT and WOW should be an element in the process of time estimation. As the work done in this thesis deal with the phases and sub-phases of drilling operations, the author recommends using the work done by Adams et al. (2009) to complete a fully probabilistic time estimate with WOW and NPT risks.

2.6.1. Waiting on Weather

Waiting on Weather, hereby denoted as WOW, is defined as stop in the operations due to bad weather or upcoming bad weather where it is not possible to finish the current operation before weather picks up to a level outside of the operational window defined (Adams A. J. et al. 2009, p. 5). WOW is an event greatly influenced by rig type and seasonal weathers. The WOW-frequency during winter season is reported to 0.594 events/TF (Trouble Free) day, while during summer season it is 0.175 events/TF-day.

2.6.2. Non-Productive Time

Non-Productive Time, hereby denoted as NPT, is defined as all other operations that is not in connection with the planned time planner develop before start-up of the drilling operations (Adams A. J. et al. 2009, p. 2). The experience presented by Adams et al. (2009) is that there does not exist any clear boundary of what NPT is but rather differ upon which drilling supervisor that is located on the rig. As the upper management provide funding based on the AFE and time estimate, all other operation beside that should be considered as NPT and this is the assumption in the Monte Carlo model presented.

3. Development of a Time Estimation Monte Carlo Model

In order to make a fully transparent time estimate with use of the Monte Carlo modelling, it is important to break down the data such that they are exclusively drilling operation data, and no factorisation of non-operational data. The data must be setup such that the drilling engineer personnel maintaining the data can easily understand the process and where to input new historical data as time elapse and new wells are drilled.

From the drilling dataset given by the company from existing wells dating less than 10 years back, three percentiles have been extracted and further used in the Monte Carlo-analysis for all the presented phases and sub-phases.

3.1. Filtration of Past Data

When a well is drilled and the raw data from each phase and sub-phase is available, the data may contain timings that is not of relevance for the probabilistic model. Waiting on Weather (WOW) and Non-productive Time (NPT) are two data points that is not of relevance for this model. The uncertain events WOW and NPT are added at a later stage in the planning process.

If the raw data is not filtered thoroughly, one may experience a double layer of timings that will lead to over-estimating, and subsequently value erosion. A WOW-event is for example a more controlled area where the engineers can base their decision making on the drilling location and weather conditions at a later stage in the project. There will be differences in WOW between a jack-up, drillship and a semi-submersible drilling unit due to how the different types are built and operates. For example, a jack-up drilling unit are more sensitive during a rig move when it comes to weather criteria and limits opposed to a semi-submersible and drillship unit. During operations, it is opposite. Where the jack-up unit has ‘legs’ extending all the way to the seabed and has a broader operational limit compared to a semi-submersible and drillship unit that floats on the sea and has a narrower weather window to operate in.

Often in a project, the selection of the drilling unit commences at a later stage opposed to preliminary time estimation. Thus, it is important to filter out the WOW- and NPT-events to make a comparable decision foundation.

3.2. Normalization of Drilling Parameters

Parameters that are variable must be normalized to create the same grounding upon simulation of new wells with different parameters and locations to make them as applicable as possible in various drilling criteria. For example, it may take 18 hours to drill the 1,200 metres long 17 ½” hole section, and by dividing the metres drilled by the total hours used one gets the ROP, which would be 66.6 m/hr. For another well, the planned length of the 17 ½” hole section is 650 metres and if 18 hours were to be used as input in the model it would give a wrong estimate.

ROP (Rate of Penetration), RIH (Running in Hole), POOH (Pulling Out of Hole) in the open-hole section and cased-hole section, and sailing speed are constants that have to be broken down from hours to m/hr, std/hr and knots. In the DDR, Daily Drilling Report, the ROPs, RIHs, POOHs and sailing speed are reported in intervals as well as total time it takes to drill the hole section from top to bottom, tripping in or out of the hole, and total time from start of sailing until arrival on location. RIH are in the drilling phases in cased hole section, and there is no risk of getting stuck into formations as in open hole section, meaning the parameters rely on how quick the driller and roughnecks can torque on new pipes. The POOH are divided into two different events; POOH Open Hole and POOH Cased Hole. Where POOH Open Hole are similar physical events just in reversed direction. For the POOH Cased Hole event, more precaution must be done as there is risks of borehole instability and swabbing and therefore std/hr tends to be reduced relatively to RIH and POOH Cased Hole. In the occasion of sailing speed, the total time from leaving location X upon arrival on the spud location and commencing anchoring or fastening, need to be converted to a velocity unit, knots. The ROP, RIH, POOHs and sailing speed events are broken down and normalized making them applicable and easy to use in future scenarios.

3.3. Risks Involved in Drilling Operations

In the early project phase, an offset analysis is prepared. The offset analysis will analyse relevant offset wells drilled nearby to the spud location that one may learn from both positive and negative experiences from the operations. Where there have been problems one wants to implement reducing measures of the sort minimizing those problems. This kicks of the initial planning of the well where number of casing strings, kind of drilling mud and type of drill bit that is going to be used. A proper offset analysis is critical for risk reducing measures.

During drilling operations there is several risks involved, all ranging from minor to major operations impact. For a well drilled in the 1980’s and another drilled in 2020 just some meters apart each other, the risks involved with drilling will not be of similar character due to technology advancement and learnings from the older well. There is therefore not convenient to use the Monte Carlo-model used in this thesis on risks in drilling operations but rather focus on quantifying the risks picture together with fellow engineers.

The risks used in the models presented in Chapter 5 Results are the same as the original time estimate derived from the offset analysis done upfront of the drilling.

3.4. Distinctive Phases & Sub-Phases

As described in Chapter 1.1, one well can be divided into several phases. One phase can further be divided into sub-phases that is essentially distinct for each phase. An example of a phase can be to drill the 36” open hole section, followed by a new phase of setting the 30” conductor casing. Below, the phases ([1],[2],[3],…,[17]) is given from start to finish for a 3-string casing design exploration well drilled with a 4th generation semi-submersible rig, with the associated sub-phases below each phase [units]:

1. Rig Move from Location X to Spud Location.
    - Tow rig from outside 500m zone of location X to spud location [knots].
    - Connect to pre-laid anchors [hours].
    - Position rig [hours].
    - Prepare to spud and pick-up drill pipe [hours].
2. Drill 36” Open Hole Section.
    - Make-up 36” BHA [hours].
    - Perform shallow gas drill [hours].
    - Drill 36” hole to TD [meters/hour].
    - Perform wiper trip [hours].
    - Displace hole to weighted mud [hours].
    - POOH and rack back BHA [meters/hour]
3. Run 30” Conductor Casing.
    - Rig-up to run 30” conductor casing [hours].
    - Pick-up shoetrack and pressure test [hours].
    - Run 30” conductor casing on running tool [joints/hour].
    - Rig-up and RIH with cement stinger [hours].
    - Attach PGB on top of 30” conductor casing [hours].

- Run and land 30” conductor on drill pipe [hours].
- Mix, pump & displace cement [hours].
- Keep the conductor casing in tension while cement harden [hours].
- Release running tool and check PGB and verify TOC [hours].
- Pull out of hole and lay down running tool [meters/hour].
- Lay-out cement head & BHA [hours].

4. Drill 17 ½” Open Hole Section.
    - Make-up 17 ½” BHA [hours].
    - Rin in hole to TOC [meters/hour].
    - Perform shallow gas drill [hours].
    - Drill out the cement in the shoetrack [hours].
    - Drill 17 ½” hole to TD [meters/hour].
    - Circulate the hole clean [hours].
    - Pull out of hole including flushing the PGB [hours].
    - Rack-back and lay down BHA [hours].
5. Run 20” x 13 3/8” Surface Casing.
    - Rig-up to run 20” x 13 3/8” surface casing [hours].
    - Pick-up shoetrack and pressure test [hours].
    - Run 20” x 13 3/8” surface casing [joints/hour].
    - Pick-up wellhead and run-in hole to land casing on landing string [hours].
    - Retrieve landing string [hours].
    - Make-up stab-in sub to drill pipe [hours].
    - Run stab-in stinger [hours].
    - Make-up cement head [hours].
    - Establish circulation & circulate casing contents [hours].
    - Pressure test the rig surface lines [hours].
    - Mix, pump & displace cement [hours].
    - Rack-back cement stand [hours].
    - Retrieve cement stinger [hours].
    - Lay-out 17 ½” BHA [hours].
    - Check for grouting on seabed [hours].
6. Run BOP & Riser.

- Rig-up to run BOP [hours].
- Make-up BOP to marine riser [hours].
- Run BOP on marine riser [meters/hour].
- Make-up slip joint and landing joint [hours].
- Install choke and kill lines [hours].
- Soft land the BOP on the wellhead [hours].
- Lay-out landing joint and install diverter [hours].
- Pressure test BOP connector and 20” x 13 3/8” surface casing [hours].
- Rig-down BOP handling equipment [hours].

7. Drill 12 ¼” Open Hole Section.
    - Make-up 12 ¼” BHA [hours].
    - Diverter & function test the BOP [hours].
    - Run-in hole to TOC inside 20” x 13 3/8” surface casing [meters/hour].
    - Perform choke/gas drill [hours].
    - Displace well to weighted mud [hours].
    - Drill out cement in shoetrack [hours].
    - Drill 3 meters of new formation and perform FIT/LOT [hours].
    - Drill 12 ¼” hole to TD [meters/hour].
    - Circulate hole clean. [hours]
    - Pull out of hole to 13 3/8” casing shoe [meters/hour].
    - Pull out of hole to top of BHA [meters/hour].
    - Rack-back 12 ¼” BHA [hours].
8. Run 9 5/8” Production Casing.
    - Make-up remote operated cement head [hours].
    - Retrieve wearbushing [hours].
    - Rig-up to run 9 5/8” production casing [hours].
    - Pick-up shoetrack and pressure test [hours].
    - Run 9 5/8” production casing [meters/hour].
    - Pick-up 9 5/8” wellhead [hours].
    - Pick-up cement stand [hours].
    - Pick-up casing hanger [hours].
    - Run-in hole with 9 5/8” casing on landing string [meters/hour].

- Make-up cement head and land casing in wellhead [hours].
- Establish circulation & circulate casing contents [hours].
- Pressure test rig surface lines [hours].
- Mix, pump & displace cement [hours].
- Rack-back cement stand [hours].
- Retrieve landing string [hours].
- Pressure test 9 5/8” production casing [hours].
- Set seal assembly and pressure test [hours].
- Release running tool and pull out of hole [hours].
- Lay-down running tool and cement stand [hours].
- Set wearbushing [hours].
- Pressure test the BOP [hours].
- Lay-down 12 ¼” BHA [hours].

9. Drill 8 ½” Reservoir Section.
    - Make-up 8 ½” BHA [hours].
    - Run-in hole to TOC inside 9 5/8” casing [meters/hour].
    - Perform choke/gas drill [hours].
    - Drill out cement in shoetrack and adjust mud weight [hours].
    - Drill 3 meters of new formation and perform FIT/LOT [hours].
    - Drill 8 ½” hole to core point [meters/hour].
    - Circulate hole clean [hours].
    - Pull out of hole to 9 5/8” casing shoe [meters/hour].
    - Pull out of hole to top of BHA [meters/hour].
    - Lay-down 8 ½” BHA [hours].
10. Coring of Reservoir.
    - Make-up coring BHA [hours].
    - Run-in hole to coring point [meters/hour].
    - Circulate bottoms-up prior to cutting core [hours].
    - Cut core [hours].
    - Circulate bottoms-up and flow check [hours].
    - Pull out of hole [meters/hour].
    - Lay-down core [hours].

- Pick-up 8 ½” BHA [hours].

11. Wireline Logging.
    - Clear rig floor and rig-up wireline [hours].
    - Make-up logging string [hours].
    - Run-in hole with logging string [meters/hour].
    - Run logging string (DOBMI-MSIP, AIT-PEX-CMR, XPT-GR, CBL etc.) [hours].
    - Pull out of hole with wireline [meters/hour].
    - Rig-down wireline [hours].
12. PP&A of Reservoir Section & Production Casing.
    - Pick-up and make-up cement stinger and stand [hours].
    - Run-in hole on drill pipe [meters/hour].
    - Circulate hydrocarbons through choke and condition mud [hours].
    - Set deep-set cement plug (primary barrier) [hours].
    - Pull above and circulate stinger clean [hours].
    - Set deep-set cement plug (secondary barrier) [hours].
    - Pull above and circulate stinger clean [hours].
    - Pull out of hole with cement stinger [meters/hour].
    - Rack-back cement stinger [hours].
    - Make-up 8 ½” junk bit [hours].
    - Run-in hole to TOC [meters/hour].
    - Pick-up BOP test tool and land in wellhead [hours].
    - Pressure test BOP and rig surface equipment [hours].
    - Run-in hole and tag top of cement plug [meters/hour].
    - Dress off and pressure test cement plug [hours].
    - Pull out of hole with cement stinger and break out bit [meters/hour].
13. Cut & Pull Production Casing.
    - Make-up 9 5/8” casing cutting assembly [hours].
    - Run-in hole to 9 5/8” casing cutting depth [meters/hour].
    - Establish circulation and perform a choke drill [hours].
    - Cut 9 5/8” casing and flow check [hours].
    - Pull out of hole with 9 5/8” cutting assembly [meters/hour].

- Lay-down 9 5/8” casing cutting assembly [hours].
- Retrieve wearbushing and flush seal assembly [hours].
- Run-in hole and release 9 5/8” seal assembly [meters/hour].
- Cross circulate with closed BOP [hours].
- Pull out of hole with 9 5/8” seal assembly [meters/hour].
- Rig-up for retrieving 9 5/8” casing [hours].
- Make-up 9 5/8” spear assembly [hours].
- Run-in hole with 9 5/8” spear assembly [meters/hour].
- Latch spear into 9 5/8” casing and pull to surface [meters/hour].
- Recover 9 5/8” casing to surface [joints/hour].
- Rig-down casing handling equipment [hours].

14. Set 13 3/8” EZSV and Cement Plug.
    - Make-up 13 3/8” EZSV assembly [hours].
    - Run-in hole to EZSV setting depth [meters/hour].
    - Set 13 3/8” EZSV, tag and pressure test same [hours].
    - Set cement plug on top of EZSV with cement stinger [hours].
    - Scrape well and displace to seawater [hours].
    - Pull out of hole above and circulate cement stinger clean [meters/hour].
15. Pull BOP & Riser.
    - Rig-up to pull BOP [hours].
    - Pull diverter tool and lay-down to deck [hours].
    - Unlatch BOP and skid rig [hours].
    - Lay-out slip joint [hours].
    - Pull BOP to moonpool [meters/hour].
    - Skid BOP out of moonpool [hours].
    - Clear rig floor for BOP equipment [hours].
16. Cut & Pull 20” x 30” Casing and Pull PGB.
    - Run-in hole and tag surface plug [meters/hour].
    - Pull out of hole [meters/hour].
    - Make-up 30” x 20” casing cutting assembly [hours].
    - Run-in hole to 30” x 20” casing cutting depth [meters/hour].
    - Cut 30” x 20” casing [hours].

- Recover and lay-down 30” x 20” casing, wellhead and PGB [hours].
- Start de-ballasting rig [hours].

17. Demob Rig from Spud Location to Location Y.
    - Disconnect anchors [hours].
    - Move rig out of 500 metres zone [knots].

In the sub-chapters below, a thorough description of each phase is given.

3.4.1. Rig Move

The rig move-phase will in most cases start off with anchor handling boats towing the rig to the specific drilling location. In some cases, dependent on rig contract types and cold- and warm-stacking of the rig, it can start with anchor handling from a green yard. As the company does not hold enough data on sub-phases in the case on operations prior to the rig being in transit, the sub-phase is neglected. Selected cases will reflect start of operations at start of transit, where the sole parameter is the velocity of the rig, in knots.

Specific for a 4th generation drilling rig with no dynamic positioning system, upon arrival on the spud location, it will connect to the pre-laid anchors set prior to start of operations. When finished connecting to the anchors, the rig is positioning using winches such the rotary table is right above spud location. At end of the phase, preparations to spud the conductor hole is done by taking up mud, if any, and picking up drillpipe.

3.4.2. Drilling Conductor Open Hole

Drilling the conductor open hole-phase defines the first section of the well and is normally drilled with a 42- or 36-inches drill bit, followed by setting a 36- or 30-inches conductor casing. First, the BHA is made up according to the casing tally followed by a toolbox talk regarding the risk of encountering shallow gas, a formal ‘shallow gas drill’. When the shallow gas drill is completed, drilling of the section will commence until TD is reached. While drilling there is risks involved that result in extra time used to drill the section. The company’s risk picture is summarized below.

- Encountering boulders.
- Hole-inclination above one degree.

Derived from previous conductor drillings, number of meters drilled drill divided by the total time it takes to reach bottom of the section, also called TD (true depth) yields the ROP. The resulting range of P90-, P50- and P10 ROP from historical drilled wells is respectively 3.56 m/hr, 9.15 m/hr and 12.6 m/hr.

Some companies have a rule to perform a wiper trip when TD is reached, and this sub-phase is added into the phase if relevant. Subsequently a wiper trip, the hole will be displaced to a weighted mud before POOH in order to have sufficient overpressure in the open hole relative to the pore pressure, and finally, racking back the BHA.

3.4.3. Running Conductor Casing

Running of the conductor casing-phase defines the first section cased of, typically a 36- or 30-inches outer diameter pipe. Firstly, rigging up to run the conductor casing followed by taking up the first joint of casing, the so-called shoetrack, and pressure testing it to make sure the float inside holds. After the pressure testing of the float, rest of the conductor casing is run in hole to TD. Associated with running of conductor casing there are involved risks as not being able to run casing to TD and cases where circulation must be done on every new joint made-up. Below, as summary of the company's risk picture when running conductor casing.

- Unable to stab-in casing.
- Re-run conductor casing.

Succeeding running of casing, the wellhead is picked- and made-up, run and landed at the seabed on a landing string. When the conductor casing is landed on seabed, the landing string is retrieved to surface.

At the surface, the stab-in stinger for cementing operations are made-up to drill pipe and RIH to prepare pumping of cement. A cement stand is made-up on surface to the drill pipe. Before pumping cementing, one establishes circulation with mud and pump 1.5-hole volume to clean up cuttings as good as possible. A pressure test of the surface lines is done before cement is mixed ready and pumped down hole into the annular space of the casing.

Upon completion of cementing, the cement stand is racked-back followed by retrieving of the cement stinger. At the drill floor, casing running equipment have been used to run the pipes up and down, and now needs to be rigged down before laying down the BHA.

3.4.4. Drilling a Pilot Hole

A pilot hole is drilled if there is any risk of shallow gas at the spud location. It commences by making-up the 9 7/8” BHA in the rotary table. After the BHA is made-up, the crew gathers in the drillers cabin to perform a ‘shallow gas drill’ and RIH to TOC (top of cement) to drill out the cement shoe before start drilling of the pilot hole. Associated with drilling of the pilot hole there are several risks involved. The probability used for each risk are derived from the offset analysis together with experience from nearby wells, the available wells in the company’s portfolio and previously experience from the drilling engineers. Each risk involved with drilling of a pilot hole is summarized below.

- Encounter shallow gas.
- Encounter boulders.
- Broken BHA and trip out to change same.
- Broken bit and trip out to change same.
- Wellbore instability while drilling or tripping.
    i. Tight hole conditions resulting in reaming.
    ii. Stuck pipe scenarios.

When TD is reached, the hole is circulated clean, and flow checked for any gas. Further displacing the 9 7/8” open hole with weighted mud to always be in overbalance with regards to the pore pressure. When the displacement is complete, the drill pipe is POOH and laid down on deck at surface.

3.4.5. Drilling Surface Open Hole

Drilling of the surface open hole-phase starts with making-up the BHA, often a 26” or 17 ½” drill bit size, depending on whether it is designed using a 3- or 4-string casings. The ROP for surface holes using a 26” and 17 ½” bit is differentiated due to its relatively big size contrast and if a pilot hole has been drilled in advance. Thereafter, drill bit is RIH to either TOC or casing shoe depending on whether the cement shoe is already drilled out or not. Drilling of the section may involve risks that is summarized below.

- Encounter shallow gas (this risk is illuminated if a pilot hole has been drilled).
- Encounter boulders.
- Broken BHA and trip out to change same.

- Broken bit and trip out to change same.
- Wellbore instability while drilling or tripping.
    i. Tight hole conditions resulting in reaming.
    ii. Stuck pipe scenarios.

When TD is reached, the hole is circulated clean for cuttings before displacing the well to a weighted mud system. Subsequently, POOH to the conductor shoe with a risk of wellbore instability effecting the pulling speed. Therefore, a different pulling speed (joints/hour) will be used for an open hole section than for pulling inside a cased hole. As the top of BHA is in the rotary, it will be racked-back.

3.4.6. Running Surface Casing

The surface casing-phase starts with rigging up the casing equipment on drill floor, picking-up the casing shoetrack and testing if the float inside holds pressure. Continuing to run casing joints until TD, with the associated risk summarized below.

- Lay-out damaged casing joint(s).
- Hole fill in the open hole section resulting in washing or a wiper trip.

Last casing joint will be the wellhead and that is RIH to seabed and landed on a landing string. This landing string is retrieved to surface before making-up stab-in stinger sub to prepare for the cement job. The cement head is made-up at the surface and the well is circulated clean once more and surface lines are pressure tested to make sure there is no leaks before the cement is mixed, pumped, and displaced with risks involved. The following risks are associated with cementing of the surface casing.

- Cement equipment failure resulting in re-cementing.
- Perform squeeze job due to error in cement job.
- Perform grouting job.

Upon completion of cement job, the cement stand will be racked-back, cement stinger retrieved, casing running equipment rigged down and BHA laid-out on deck.

3.4.7. Setting BOP on Subsea Wellhead

Setting of the BOP on the surface casing foundation defines the phase full well integrity will be made, with several barriers. It starts by rigging-up to run the BOP where it is normally skidded from a storage place in the moonpool area to over sea. When BOP is over sea it will be made-up to marine riser joints down to seabed and landed on the wellhead. Choke- and kill lines will be installed, as well as other BOP equipment.

To confirm the well integrity, the BOP, riser joints and surface casing will be pressure tested up to a pre-defined pressure with the following risks involved.

- Leak in marine riser joints.
- Leak in conduit lines.
- Leak in BOP rams.
- Leak in surface casing.

3.4.8. Drilling Intermediate Open Hole

Drilling of the intermediate open hole-phase are typically drilled with a 17 ½” or 16” drill bit size. The intermediate phase is only absent for casing design with 4 or more strings.

First, the BHA will be picked-up and RIH before a diverter and function test of the BOP will materialize. Thereupon, RIH through the BOP to TOC, displace the wellbore with correct mud ready to drill out the cement shoe and perform either a LOT (leak-off test) or FIT (formation integrity test). After a successful LOT/FIT, the hole will be drilled to TD with following risks.

- Broken BHA and trip out to change same.
- Broken bit and trip out to change same.
- Wellbore instability while drilling or tripping.
    i. Tight hole conditions resulting in reaming.
    ii. Stuck pipe scenarios.
- Losses to fault zone while drilling.

At TD, the hole will be circulated clean for cuttings before POOH commence. First, POOH to surface casing shoe with less joints per hour compared to POOH from casing shoe to top of

BHA. There is a risk of tight hole while tripping out in the open hole section. At surface, the BHA will be racked-back.

3.4.9. Running Intermediate Casing

Running of the intermediate casing-phase frequently represents use of a 13 3/8”, 13 5/8” or 14” casing, and in some cases a liner. First starts with making-up the remote operated cement head, retrieving the nominal bore protector and rigging-up surface equipment to run casing. The casing shoetrack is picked-up and pressure tested before rest of casing is RIH. Risks associated with running in hole are:

- Lay-out damaged casing joint(s).
- Hole fill in the open hole section resulting in a washing or wiper trip.

When casing is reached TD and landed in wellhead, circulation will be established to clean up contents inside before pressure testing the surface lines. Cement will be mixed, pumped, and displaced downhole. A pressure test will take place when the cement has hardened and if good pressure tests the running tool will be POOH and laid-down on deck together with the cement stand. All casing running equipment will be rigged-down before the wear bushing is set, and BHA will be laid-down in the end.

3.4.10. Drilling Production Open Hole

Drilling of the production open hole-phase is normally done with a 12 ¼” drill bit size but changes dependent on formation requirements, casing design and cost picture. Starting with making-up the BHA, doing a diverter and function test of the BOP and RIH to TOC. This phase has a significant risk of drilling into hydrocarbons; therefore, a choke drill exercise is done before displacing well to the planned mud weight and drilling out the cement shoetrack. A LOT/FIT will be performed below the production casing shoe before drilling of the section to TD. Risks involved with the drilling are:

- Broken BHA and trip out to change same.
- Broken bit and trip out to change same.
- Wellbore instability while drilling or tripping.
    i. Tight hole conditions resulting in reaming.
    ii. Stuck pipe scenarios.

- Losses to fault zone while drilling.
- Encounter a gas kick.

At TD, the hole will be circulated clean before POOH in two stages, one to the previous casing shoe and other from the shoe to top of BHA, and finally racking-back the BHA.

3.4.11. Running Production Casing

The production casing-phase commence the last casing string set before entering the reservoir in most cases. In some cases, a production liner is also set, which enclose the same sub-phases together with a few differences.

Casing running-phase commence by making-up the operated cement head in drill floor, retrieving the nominal bore protector, rigging-up casing running equipment then picking-up and pressure testing the casing shoe. The production casing will then be run to TD where casing hanger will be picked-up at the end and landed in wellhead. Risk associated with running of the production casing are the following.

- Lay-out damaged casing joint(s).
- Hole fill in the open hole section resulting in a washing or wiper trip.

At TD, the hole will be circulated clean before pressure testing the surface lines and preparing to start cement job. Cement will be mixed, pumped, and displaced in the casing annulus ahead of pressure testing the casing to the pre-defined section design pressure. Subsequently, the seal assembly will be set, and pressure tested ahead of POOH with running tool and laying-down the same together with the cement stand. A nominal bore protector will be set in the wellhead before casing running equipment will be rigged-down and BHA laid-down on deck. Before drilling of new section, a BOP test will be done.

3.4.12. Drilling Reservoir Section

Drilling of the reservoir section defines the phase where potentially hydrocarbons are to be found for exploration and appraisal wells. For production wells, the presence of hydrocarbons is certain to a degree. Due to this, extra planning and cautions have been done in the planning phase.

The phase commences by making-up the BHA, normally an 8 ½”, before RIH to TOC. Before drilling out the cement in the shoetrack and displacing hole to the planned mud, a choke drill is done with the rig crew to prepare for influx. Succeeding drilling out shoetrack, a LOT/FIT are performed prior to drilling the hole to TD. Risks involved with the explained procedure are:

- LOT/FIT too low, squeeze cement plug.
- Broken BHA and trip out to change same.
- Broken bit and trip out to change same.
- Wellbore instability while drilling or tripping.
    i. Tight hole conditions resulting in reaming.
    ii. Stuck pipe scenarios.
- Losses to fault zone while drilling.
- Encounter a gas kick.

At TD, the hole will be circulated clean for cuttings and flow checked for gas and oil readings before POOH with the string, finally racking-back the BHA.

3.4.13. Wireline Logging

Wireline logging is a phase done to continuously measure formation properties and get richer data from the reservoir to further make better decisions about future development. It is done after cuttings have been drilled out and it is a free open hole section. Electric tools are run downhole on a wire with relatively high running speed compared to running pipes or drilling speeds.

A wireline logging string can be composed of different tools, some examples are given below:

1. Modular Dynamic Formation (MDT) Fluid Sampler.
2. Sidewall Corer.
3. Vertical Seismic Profiling (VSP) Log.
4. Cement Bond Log (CBL).
5. Caliper Log.
6. Directional Log.
7. Dipmeter Log.

Each log has different user areas and timings used to both make-up and run the tools string. In this thesis, each wireline log is divided into their respective database of historic timings. It is made such the access to the data are easy and maintenance are not complex.

The operational steps for running a wireline log starts with clearing rig floor and making-up the wireline tool string before RIH to the start measurement point, commencing logging. There are risks involved with wireline logging, summarized below.

- Tool failure and must do a re-run.
- Wireline string stuck and must cut and fish logging string.

Logging is thereupon done covering the pre-defined interval before POOH to drill floor.

3.4.14. PP&A of Reservoir Section & Production Casing

For exploration and appraisal wells, they will in most cases be permanently plugged and abandoned after the main objective is met, which is to get reservoir data to further conclude on development or not. P&A-operations are timely and cost intensive.

PP&A of the reservoir section and production casing starts with picking- and making-up the cement stinger and stand before RIH. At TD, the hole will be circulated clean prior to pumping in cement barrier number #1 and #2 according to the P&A-plan. Depending on the length of the cement plug, it can be set in two or more stages. Finalizing pumping of cement, the cement stinger will be pulled above TOC and circulated clean before POOH.

At surface, the cement equipment is racked-back, and a junk drill bit are made-up and RIH to TOC to tag the cement plug and verifying the hardness. A pressure test will be done if successful tagging to make sure the plug withholds abandonment pressures. To conclude the PP&A of the reservoir section and production casing, the junk drill bit is POOH and laid-back.

3.4.15. Cut & Pull Production Casing

According to NORSOK D-010 ‘’… the wellhead and casings shall be removed below the seabed at a depth which ensures no stick up in the future’’. To be able to cut the wellhead and remove same, one must cut the production casing to get access to the intermediate, if any, surface, and conductor casing.

A cutting assembly specific for the casing size are made-up on surface and RIH to the cutting depth. Once cutting depth are reached, circulation is established, and a choke drill are performed. The cutter starts and upon indication of a confirmed cut, a flow check will be done to make sure there is communication between the hole and production casing annulus. If communication is confirmed, the assembly will be POOH and laid-down before retrieving the nominal bore protector and flushing along with releasing of the seal assembly in the wellhead.

The casing running equipment will be rigged-up on the drill floor and a spear assembly RIH to the cut depth and activated. Spear will be latched into the casing and pulled to rotary. Upon completion of retrieval, the casing handling equipment will be rigged down.

3.4.16. Cut & Pull Intermediate Casing

If the well had four or more casing strings, the intermediate casing would also need to be cut and pulled out of hole. It will start of by RIH and setting the nominal bore protector before the same procedure follow as for cutting and pulling the production casing. The intermediate casing will have a cutting depth that is shallower than the production casing.

3.4.17. Setting of EZSV & Cement Plug

Setting of the EZSV and a cement plug on top of it describes the environmental plug. The EZSV will be set inside of the surface casing and are not a regulatory requirement but rather a precautionary measurement.

The phase start with making-up the EZSV assembly and RIH to the setting depth before setting it. The EZSV will be tagged, and pressure tested according to NORSOK D-010 to make sure I withhold abandonment loads. Cased hole above the EZSV will be displaced to seawater before pumping a cement plug on top of it. The cement stinger will be circulated clean, POOH and laid-back.

3.4.18. Pull BOP & Riser

At this stage, the drilled well got all well barriers in place to take of the well control equipment. After rigging-up to pull the BOP, the diverter will be pulled and laid-down on deck before unlatching of BOP and skidding rig away from well centre preparing to bull BOP to surface.

When BOP is retrieved at surface, a clean-out run will be done before clearing the rig floor for BOP equipment.

3.4.19. Cut & Retrieve Surface & Conductor Casing

Before cutting and retrieving the surface and conductor casing, a junk drill bit is RIH to tag a hardened environmental cement plug and POOH when confirmed. The cutting assembly will then be made-up on surface ahead of RIH to cutting depth and commence cutters. If successful cut, the surface and conductor casing, wellhead and PGB will be recovered to surface and laid down for scrapping. Straight afterwards the rig will start de-ballasting to prepare for rig move.

3.4.20. Demob Drilling Rig

When rig is de-ballasted and anchors are disconnected, the rig will be towed out of its 500 metres zone ending the rig contract. The AFE for the drilling phase will hereafter be ended.

PART II

CASE SIMULATION, RESULTS & ANALYZING

4. Case Studies

A comparison of four different time estimates for exploration wells drilled by Wellesley Petroleum AS, hereafter called Wellesley, will be shown in this chapter to display how the MC-model performs against the traditional estimate, a 3rd party time estimate method and actual time used drilling. A summary of the following four time estimate methods will be presented:

1. Traditional Deterministic Method:
   - Deterministic method using cognitive and biased data.
2. Monte Carlo Probabilistic Method:
   - Probabilistic MC-method utilizing historical data.
3. 3rd Party Time Probabilistic Method:
   - Independent probabilistic time estimate with no use of historical data.
4. Real Time Drilling:
   - The actual time used to drill the well. Will function as the comparative goal.

4.1. Case 1 – Schweinsteiger Exploration Well

4.1.1. Background

The Schweinsteiger well, 6204/11-3, was a prospect in PL829 drilled 60 kilometres north-west for Florø in 2020 by Wellesley. Results from the well showed a 30-metre water-wet column of sand classified as a dry well. It was drilled by the 4th generation drilling rig Borgland Dolphin and got permanently plugged and abandoned after finishing data gathering from the well.

A WOW- and NPT-risk of 12 and 8 percentages are added on top of the modelled estimates.

4.1.2. Traditional Deterministic Method

Based on bias and intuitive information from the engineers designing the well, in cooperation with service providers to understand the equipment and risks involved, a deterministic time estimate was made as input to the AFE.

The traditional time estimate was based on learnings from the previously wells and used as intuitive data inputted into the estimate. Normally, the estimate contains a P90 and a P50, also called the budgeted time, which in technical terms is regarded as the P90- and P50-percentiles. One notes that there is no estimate of the P10-percentile, as valid from the figure below.

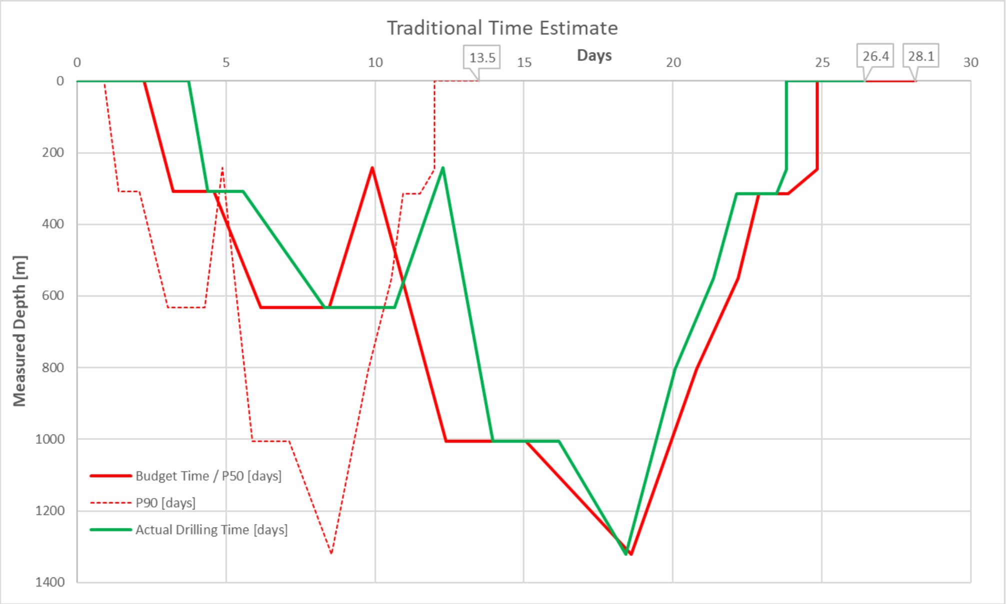


Figure 11: Traditional Time Estimate for Schweinsteiger

The figure shows a time versus depth relationship for the planned Schweinsteiger well. On the y-axis, one can see the measured depth reached during drilling, ranging from surface to the true drilled depth, and the x-axis is counting number of days for the well, starting with zero days to end of rig contract. Budget time predicts a total of 28.1 days while the P90-percentile predicts 13.5 days from start to finish. Below, a more detailed graph only showing the budgeted time (P50) for the traditional way of doing a time estimate.

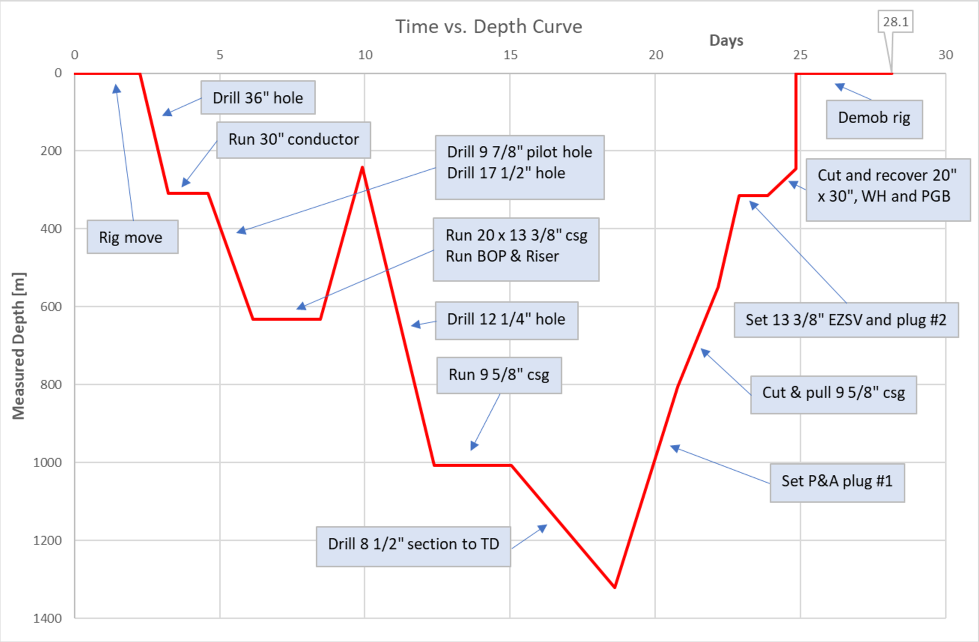


Figure 12: Detailed Traditional Time Estimate for Schweinsteiger

The graphical representation above shows physically where each phase fits with regards to the timeline as described in Chapter 3. The phase-visualisations for the different models, as in the figure above, will be left out for the remaining part of the thesis.

4.1.3. 3rd Party Time Estimate

A time estimate using a 3rd party software have been used to compare with. The same cognitive biased data as in the traditional deterministic method have been used in the model applying a 3-point distribution together with Monte Carlo simulations.

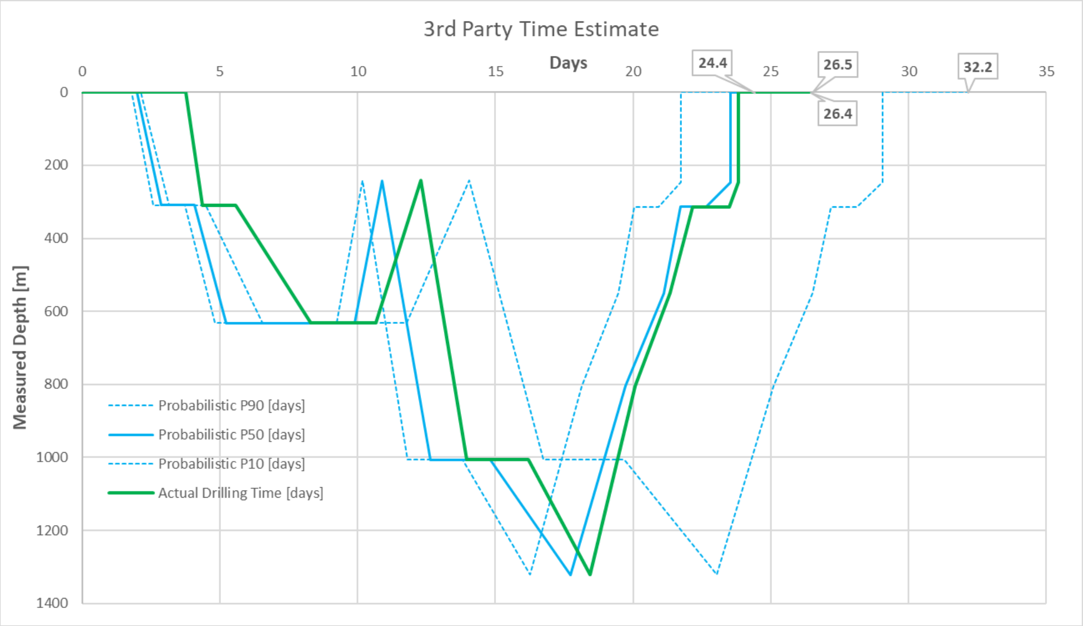


Figure 13: 3rd Party Time Estimate for Schweinsteiger

The outputs are the P90-, P50- and P10- Monte Carlo percentiles respectively yielding 24.4, 26.5 and 32.2 days from start to end of the well. A narrower window between the P90- and P50-percentiles relatively to the historical data based-Monte Carlo model are observed, while the upper limit is of less days.

4.1.4. Monte Carlo Probabilistic Method

The described Monte Carlo time estimate leveraging data and statistics have been back-engineered then fitted to the Schweinsteiger well to show how the model performs. The main objective of such model is to give a probabilistic based range for the decision maker(s) to optimize the overall decision process.

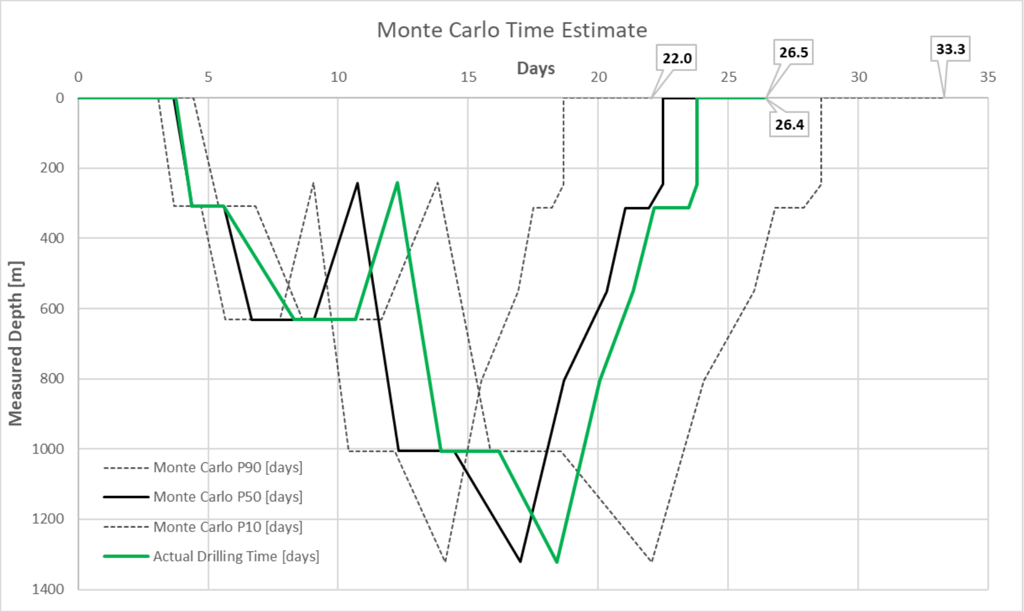


Figure 14: Monte Carlo Time Estimate for Schweinsteiger

From Figure 10 it is observed that the P90-, P50- and P10-scenario generate drilling timings of respectively 22.0, 26.5 and 33.3 days. One recognizes the P50 estimate is more towards the P90-estimate than the P10, fitting the theory described in Chapter 2.1.1.

4.1.5. Real Time Drilling

Without any unforeseen events happening while drilling Schweinsteiger, time used to drill the well should be between the P90- and P10-percentiles. In the figure below, the actual time used to drill the Schweinsteiger well is shown, with a final drilling time of 26.4 days.

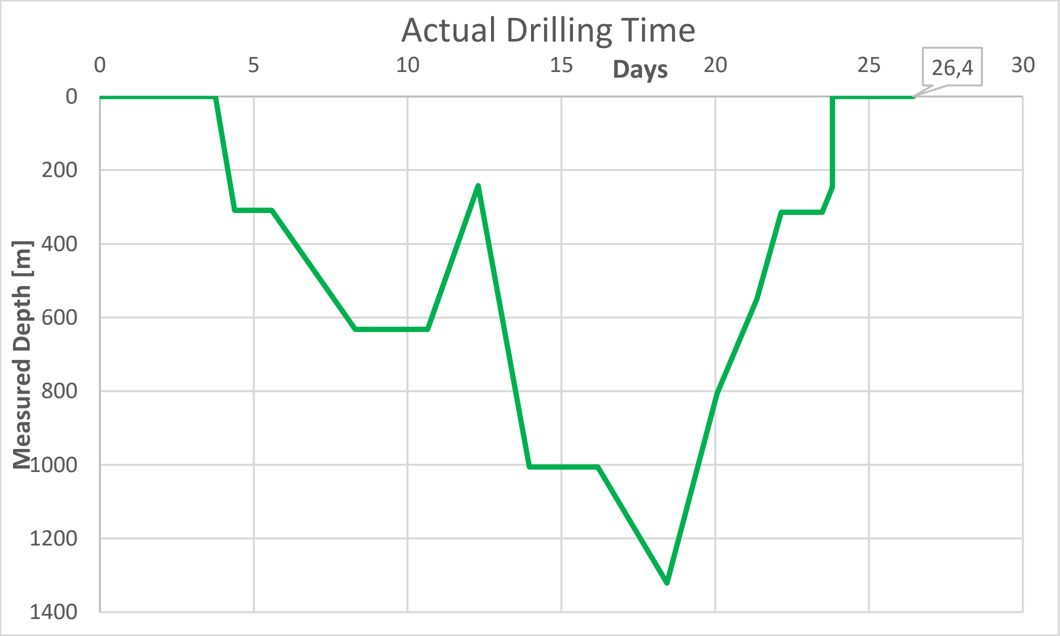


Figure 15: Actual Drilling Time Used on Schweinsteiger

4.2. Case 2 – Grosbeak West Exploration Well

The presented model in this thesis work is further implemented on another well to demonstrate how it performs. The results and comparison of the four different time estimate methods are shown in the subsequent sub-chapters.

4.2.1. Background

The Grosbeak prospect drilled in 2018 by Wellesley contains two wells, 35/11-21A and 35/11-21S, where a mainbore and a sidetrack was drilled to strengthen data collection in the area. Results from the wells showed a gross oil column of 90 metres. It was drilled by the 4th generation drilling rig Transocean Artic and got permanently plugged and abandoned after finishing data gathering from the well.

A WOW- and NPT-risk of 6 and 3 percentages are added on top of the modelled estimates.

4.2.2. Traditional Deterministic Method

Shown time estimate below is done in the same way as the described deterministic method as for Schweinsteiger, biased and intuitive information comprehending the drilling scope. There is given to values, a P90-percentile together with a P50. One notes that there is no estimate of the P10-percentile.

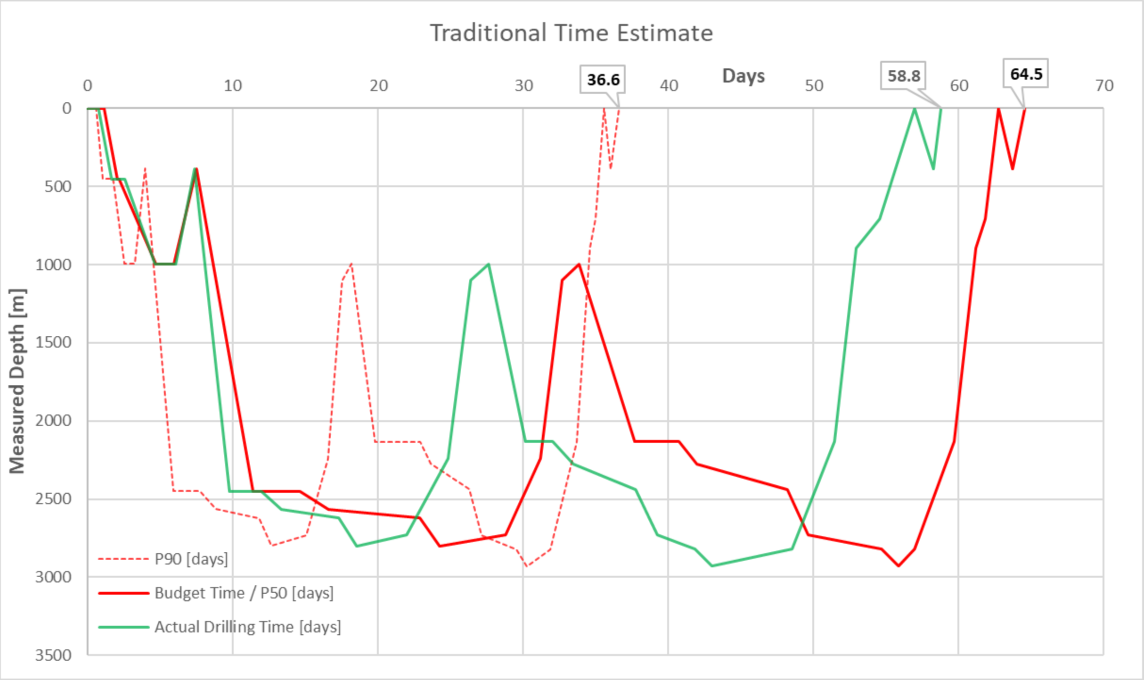


Figure 16: Traditional Time Estimate for Grosbeak West

The time- and depth relationship for the two drilling estimates shows that the P90-estimate is somehow half of the budgeted time, similar to the traditional Schweinsteiger one. It is observed that the estimate deviates from both estimated curves. The P90- and P50-estimates are 36.6 and 64.5 days, opposed to the actual time used in the operations of 58.8 days.

4.2.3. 3rd Party Time Estimate Method

The 3rd party software is used to compare, as done for the Schweinsteiger well. The same dataset is used as the traditional deterministic method together with the 3-point distribution method along with Monte Carlo simulations.

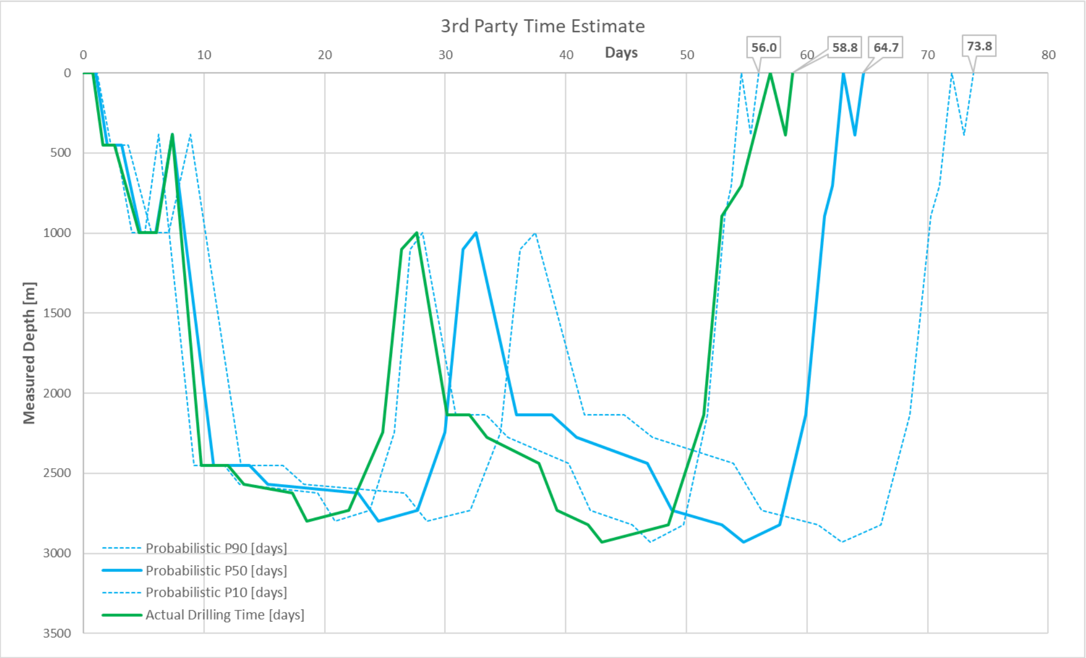


Figure 17: 3rd Party Time Estimate for Grosbeak West

The P90-, P50- and P10-percentiles yields respectively 56.0, 64.7 and 73.8 days for the well from start to finish. It is observed that the actual drilling time follows the P50-percentile in the beginning before worse drilling performance are shown and a shift to P90 and beyond that is observed. It finishes between the P90- and P50-percentile. P50-percentile lays in middle of both the P90- and P10-percentiles.

4.2.4. Monte Carlo Probabilistic Method

With the use of historical drilling performance together with Monte Carlo simulations, a probabilistic time estimate was made for the Grosbeak West well.

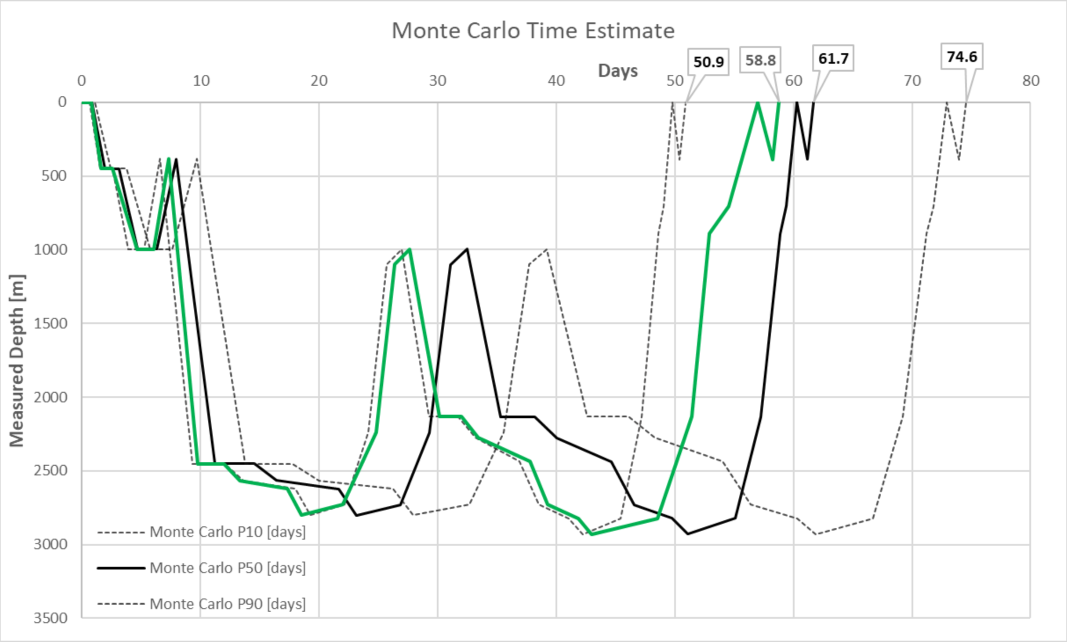


Figure 18: Monte Carlo Time Estimate for Grosbeak West

As shown for the two presented models above, the actual time used drilling outperforms the P50-estimate. The presented model aligns well with the others but has a wider distribution room of probabilistic timings.

4.2.5. Real Time Drilling

During drilling of the Grosbeak West well, no unpredicted events causing big time delays happened, and will statistically, as for the Schweinsteiger well, be between the P90- and P10-percentiles. In the figure below, the actual time used to drill the well was 58.8 days.

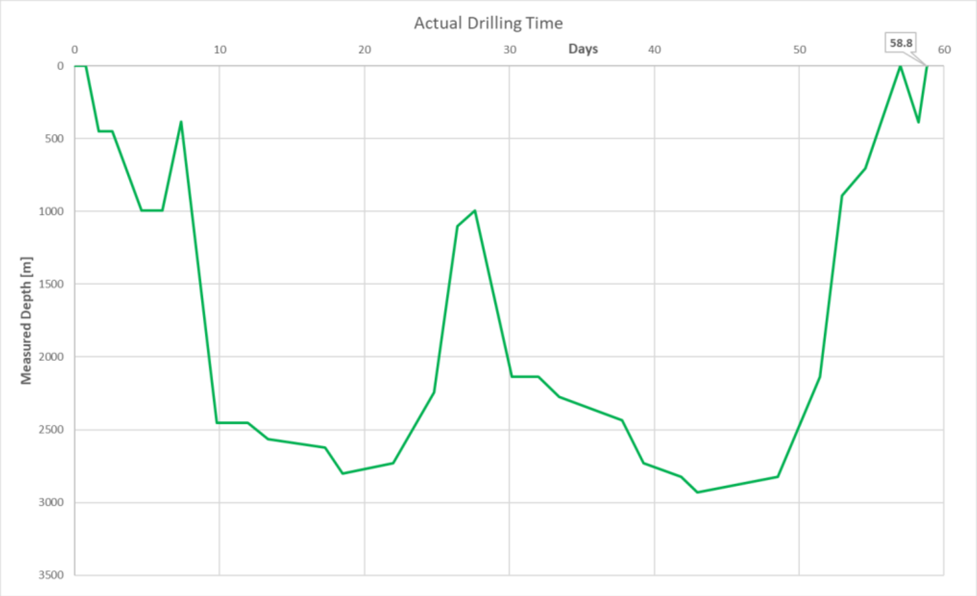


Figure 19: Actual Drilling Time Used on Grosbeak West

PART III

Probabilistic Model Evaluation & Results

5. Results

A presentation of the field case studies comparison done in Chapter 4 will be covered in this section. The built Monte Carlo-model are compared with the traditional time estimates used during planning and another 3rd party time estimate software against the actual time used to drill the wells. The relative comparison will be used as a reference together with the figures presented in Chapter 4 for the different models shown for each of the case studies and their performance will be discussed.

A relative error of the actual time drilled, and the P50-percentile estimate are done to see how well the expected time of each method matches the actual drilling time. According to the central limit theorem, the P50-percentile has a higher probability of occurring than the P90- and P10-percentiles. The following relative calculation are used:

$$\delta_{error} = \left|\frac{v_A - v_E}{v_E}\right| \times 100\% \tag{10}$$

Where,

δ_{error} = Percentage error

v_A = Actual drilling time

v_E = Expected drilling time

5.1. Comparison of Error on Schweinsteiger Estimates

A relative error comparison for each phase for the Schweinsteiger exploration well is summarized in the table below.

Table 1: Relative Error for the Schweinsteiger Well

Drilling Phase	Traditional Deterministic Method	3rd Party Probabilistic Method	Monte Carlo Probabilistic Method
Rig Move	67.4%	87.3%	2.3%
36” Open Hole	36.8%	27.1%	13.4%
30” Conductor Casing	12.1%	1.4%	1.0%
9 7/8” Pilot Hole	75.1%	139%	158%

17 ½” Open Hole	3.5%	70.9%	1.7%
13 3/8” Surface Casing	6.0%	22.5%	2.7%
Run BOP	13.8%	61.4%	1.4%
12 ¼” Open Hole	32.6%	5.2%	4.1%
9 5/8” Production Casing	16.6%	2.7%	4.9%
8 ½” Open Hole to TD	36.9%	22.7%	12.4%
P&A 8 ½” Open Hole	24.9%	18.3%	2.2%
C&P 9 5/8” Production Casing	7.3%	7.2%	22.2%
Set 13 3/8” EZSV	12.6%	27.1%	13.9%
Pull BOP & Riser	34.7%	45.8%	48.4%
C&R 20” x 30” Casings	66.3%	62.8%	41.4%
Demobilize Rig	20.0%	11.7%	33.7%
Average error	**29.2%**	**38.3%**	**22.7%**

From the table above, it is valid that the Monte Carlo method is more accurate in absolute terms, but one can see the highest deviation comes from the same method, the proposed Monte Carlo method. It has a relatively small error for each phase except for drilling of the 9 7/8” pilot hole. During drilling of the pilot hole something unexpected happened, which was included as a risk but not a certainty. Each phase has a set of probability-based risks and if they are all weighted correctly the risked time will be equal to the total added time due to unexpected happenings, as seen from Figure 12.

The traditional deterministic method performs better than the 3rd party probabilistic method when it comes to relative error but looking at Figure 10 and 11, the final time deviates more.

5.2. Comparison of Error on Grosbeak West Estimates

A relative error comparison for each phase for the Grosbeak West exploration well is summarized in the table below.

Table 2: Relative Error for the Grosbeak West Well

Drilling Phase	**Traditional Deterministic Method**	**3rd Party Probabilistic Method**	**Monte Carlo Probabilistic Method**
Rig Move	30.7%	22.3%	8.0%
36” Open Hole	6.0%	8.2%	19.3%
30” Conductor Casing	27.6%	23.7%	20.6%

17 ½” Open Hole	19.7%	29.2%	29.7%
13 3/8” Surface Casing	11.1%	13.0%	12.4%
Run BOP	12.5%	2.8%	20.8%
12 ¼” Open Hole	37.4%	29.0%	25.7%
9 5/8” Production Casing	33.9%	27.1%	35.0%
8 ½” Open Hole to CP	30.7%	9.7%	25.8%
Core Mainbore	36.6%	47.2%	24.8%
8 1/2" Open Hole to TD	13.0%	25.6%	16.0%
Open Hole Logging Mainbore	23.1%	7.5%	7.3%
P&A 8 1/2" OH	18.2%	24.0%	18.8%
C&P 9 5/8" Casing	5.2%	5.6%	13.5%
Set KOP in OH below 13 3/8"	6.8%	8.8%	9.3%
12 1/4" Open Hole ST	33.5%	23.4%	10.1%
9 5/8" Production Casing ST	39.9%	37.2%	37.1%
8 1/2" Open Hole to CP #1 ST	12.3%	29.9%	22.1%
Core Reservoir #1 ST	30.0%	26.4%	5.1%
8 1/2" Open Hole to CP #2 ST	1.1%	28.4%	25.4%
Core Reservoir #2 ST	49.0%	37.6%	17.9%
8 1/2" Open Hole to TD ST	0.3%	34.5%	16.9%
Open Hole Logging ST	391%	84.2%	39.8%
P&A 8 ½” Open Hole	9.4%	33.4%	36.5%
C&P 9 5/8” Production Casing	0.3%	4.3%	11.0%
Set 13 3/8” EZSV	145%	153%	219%
Pull BOP & Riser	157%	162%	167%
C&R 20” x 30” Casings	36.5%	38.9%	49.2%
Demobilize Rig	34.4%	21.6%	0.8%
Average error	**43.2%**	**34.4%**	**32.6%**

The Monte Carlo method is more accurate in absolute terms when fitting the dataset on the Grosbeak West exploration well. A lower accuracy is shown for this comparison opposed to the Schweinsteiger well.

6. Conclusion

This thesis covers the theoretical part of deterministic and probabilistic time estimation in drilling operations, which is the costlier part in oil and gas industry. Due to its relatively high-cost part, the focus on good estimates should be emphasized and favourable methods should be used as the decision basis when presented to the management. A proposition using a probabilistic method leveraging data and Monte Carlo simulation has been proposed opposed to the presented methods used today. A comparison between three different models is shown and it is recommended one method to use in the future.

The three methods used to compare with are:

- A traditional deterministic method.
- A 3rd party probabilistic method using Monte Carlo simulations on the same dataset as the traditional deterministic method but with the use of a 3-point distribution model.
- A new proposed probabilistic method leveraging historical drilling data with the use of Monte Carlo simulations.

The relative error comparison using the central limit theorem shows improvement with less error compared to the two other methods. It shows the advantage of using historical datasets to estimate the future with probability ranges.

In today’s world where data driven models are highlighted and preferred to make probabilistic decisions and increase value, the presented Monte Carlo model using rich data from real-time operations opposed to biased and heuristic data are featured as the favoured one to use. The model has been compared with two wells drilled by Wellesley Petroleum and it performs well giving a broader probabilistic range compared to the two other methods.

The study shows positive results implementing historical data to make drilling time estimates. A limitation with two compared wells will not display the advantage with the presented model but rather give an interpretation of how it works and what it leverages. In the short-term picture, the probabilistic Monte Carlo-model may not outperform the two others but will in a bigger picture and with more data increase the value.

It is recommended to use the model in a bigger scale, for example a larger development project with several templates and/or wells, to fully gain value from it.

7. Further Work

To further improve the proposed Monte Carlo-model one must continuously update it with new drilling data and compare the model's performance over time with more wells to see the improvement in a larger picture and how that impacts the company in decision making. Over time, with data driven decisions, the value erosion should decrease together with higher return on investment. It is therefore important to validate the model over time and improve it.

When amount of data is no restriction, it is possible to further update the model solely using nearby drilling data and offset experiences, sanctioning data based on specific drilling rigs and not only by generation type, opposed to the shown model utilizing drilling data on NCS.

In summary, the following are proposed as further work to increase value generating decision making in time estimates for drilling operations:

1. Test the Monte Carlo model on more wells for quality assurance and control.
2. Implement the Monte Carlo model shown in this thesis.
3. Collect more and richer drilling data.
4. Sanction the drilling data into location specific areas for better risk modelling.
5. Isolate drilling data into rig specific timings.
6. Use AI together with seismic data to look for formation specific risks.

8. Proposed Monte Carlo Model Limitations

Due to limitations within the company, the access is restricted to below 20 wells to extract and use data of. The more available data, richer models can be made. As quoted by Suhail Doshi, “Most of the world will make decision by either guessing or using their gut. They will be either lucky or wrong”. Together with more data the model will be better.

The performance of the Monte Carlo model is only compared with two wells and shows promising results based on that, but further evaluations must be done to make sure that the fitting is not a coincidence.

Well Expertise is a well management company helping the smaller exploration and production companies in Norway to drill exploration, appraisal, and development wells. Due to non-disclosure agreements, all the dataset used in the model cannot be given out. It has also been tried retrieving drilling data from larger E&P-companies in Norway without success.

Sharing data between companies are important to get access to enough data points. Each E&P-company in Norway have from one to several wells a year, and by utilizing the data from all drilled wells across the companies, one can achieve maximum leveraging of the data and increase value.

References

---

1. Adams, AJ, Gibson, C, Smith, R, 2009, ‘Probabilistic Well Time Estimation Revisited’, *Society of Petroleum Engineers*.

2. Bratvold, RB, and Begg, SH, 2010, ‘Making Good Decision’, *Society of Petroleum Engineers*.

3. Busenitz, LW, and Barney, JB, 1997, ‘Differences Between Entrepreneurs and Managers in Large Organizations: Biases and Heuristics in Strategic Decision-Making’, *Elsevier Science Inc*, Journal of Business Venturing, vol. 12(1), pp. 9-30.

4. Caso, C, Bennett, P, Isaachsen, J, Ask, KK, Stray, T, Andresen, PA, Straumsheim, CF, 2020, ‘Toward the Redefinition of Drilling Plan and Execution Via a Digital Drilling Ecosystem’, *Society of Petroleum Engineers*.

5. Coelho, DK, Roisenberg, M, Filho, PJF, and Jacinto, CMC, 2005, ‘Risk Assessment of Drilling and Completion Operations in Petroleum Wells Using a Monte Carlo and a Neural Network Approach’, *Federal University of Santa Catarina*.

6. Hiorth, A, ‘Modeling and Computational Engineering’, *The National IOR Centre & Institute for Energy Resources*.

7. LaValle, S, Lesser, E, Shockley, R, Hopkins, MS, Kruschwitz, N, 2011, ‘Big Data, Analytics and the Path From Insight to Value’, *MIT Sloan*, vol. 52, no. 2.

8. Løberg, T, Arild, Ø, Merlo, A, D’Alesio, P, 2008, ‘The How’s and Why’s of Probabilistic Well Cost Estimation’, *Society of Petroleum Engineers*.

9. Mireault, R, 2013, ‘Aggregate Production Forecasts for Unconventional Resources Drilling Locations Using Monte Carlo Simulation’, *Society of Petroleum Engineers*.

10. Mohus, E, 2018, ‘Over Budet, Over Time, and Reduced Revenue, Over and Over Again – An Analysis of the Norwegian Petroleum Industry’s Inability to Forecast Production’, *University of Stavanger*.

11. NORSOK D-010, 2021, ‘Well integrity in drilling and well operations’, 5th ed., *Standards Norway*.

12. Kalos, MH, and Whitlock, PA, 2008, ‘Monte Carlo Methods’, 2nd ed., *WILEY-VCH Verlag GmbH & Co. KGaA.*

13. Kerr, R, 1997, ‘DICE, The Central Limit Theorem, And Why Oil Companies Underestimate Reserves’, *Society of Petroleum Engineers*.

14. Snøtun, H, 2016, ‘Using Data to Create Foresight And Create Value From Volume’, *Society of Petroleum Engineers*.

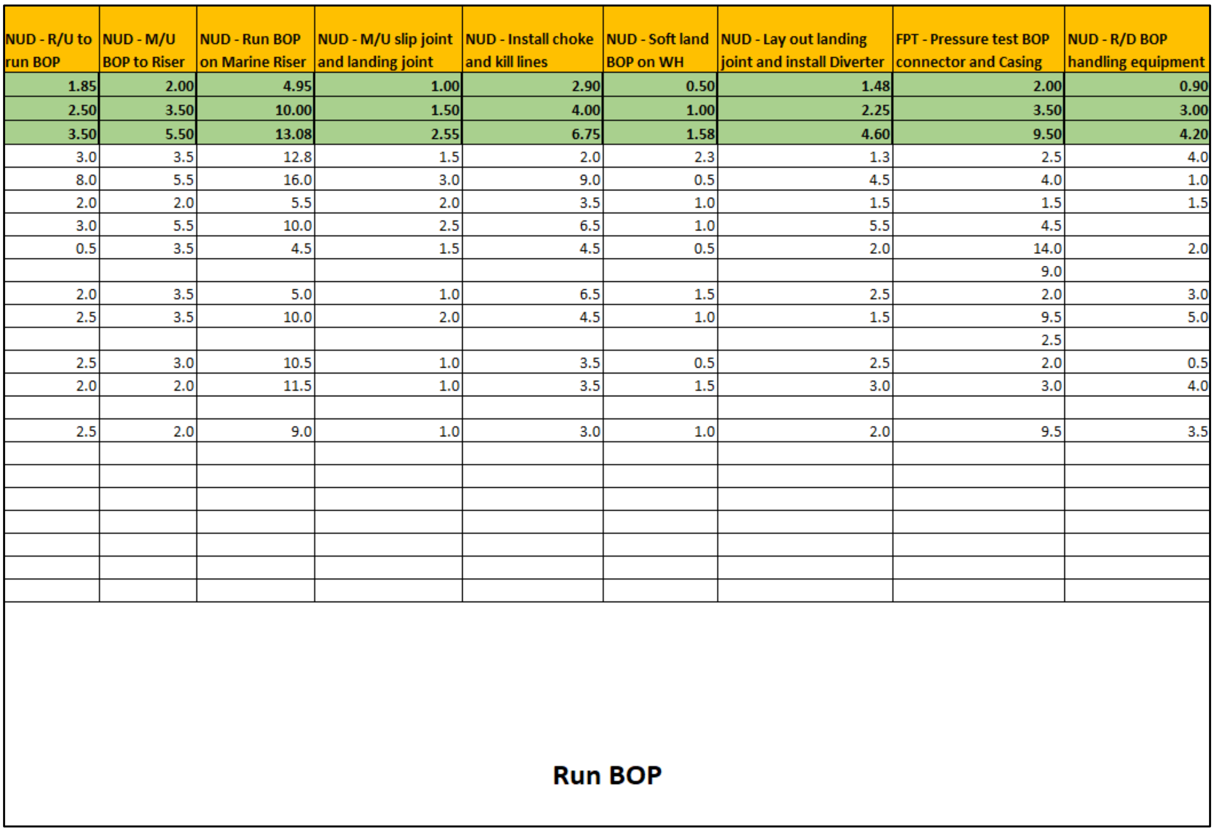
15. Stein, WE, Keblis, MF, 2008, ‘A new method to simulate the triangular distribution’, *Elsevier Ltd*, Mathematical and Computer Modelling 49 (2009) 1143-1147.

16. Peterson, SK, Murtha, JA, and Roberts, RW, 1995, ‘Drilling Performance Predictions: Case Studies Illustrating the Use of Risk Analysis’, *Society of Petroleum Engineers*.

Appendix

A1 Example of Historical Data Set – Running of BOP

Below, an example of timings used in the presented Monte Carlo model are shown. In the column missing



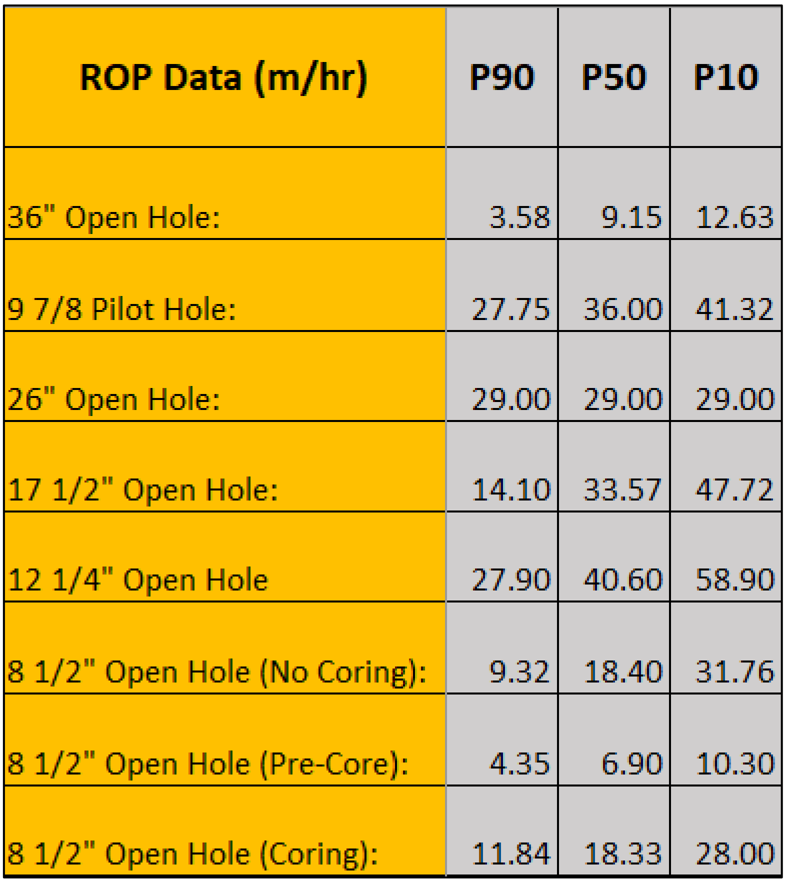
NUD - R/U to run BOP	NUD - M/U BOP to Riser	NUD - Run BOP on Marine Riser	NUD - M/U slip joint and landing joint	NUD - Install choke and kill lines	NUD - Soft land BOP on WH	NUD - Lay out landing joint and install Diverter	FPT - Pressure test BOP connector and Casing	NUD - R/D BOP handling equipment
1.85	**2.00**	**4.95**	**1.00**	**2.90**	**0.50**	**1.48**	**2.00**	**0.90**
2.50	**3.50**	**10.00**	**1.50**	**4.00**	**1.00**	**2.25**	**3.50**	**3.00**
3.50	**5.50**	**13.08**	**2.55**	**6.75**	**1.58**	**4.60**	**9.50**	**4.20**
3.0	3.5	12.8	1.5	2.0	2.3	1.3	2.5	4.0
8.0	5.5	16.0	3.0	9.0	0.5	4.5	4.0	1.0
2.0	2.0	5.5	2.0	3.5	1.0	1.5	1.5	1.5
3.0	5.5	10.0	2.5	6.5	1.0	5.5	4.5	
0.5	3.5	4.5	1.5	4.5	0.5	2.0	14.0	2.0
							9.0	
2.0	3.5	5.0	1.0	6.5	1.5	2.5	2.0	3.0
2.5	3.5	10.0	2.0	4.5	1.0	1.5	9.5	5.0
							2.5	
2.5	3.0	10.5	1.0	3.5	0.5	2.5	2.0	0.5
2.0	2.0	11.5	1.0	3.5	1.5	3.0	3.0	4.0
2.5	2.0	9.0	1.0	3.0	1.0	2.0	9.5	3.5

Run BOP

Figure 20: Historical Timing for BOP Running

A2 Example of Historical Data Set – Rate of Penetration

Below, the extracted ROPs from each well for specific sections are shown. These percentiles are further used in the Monte Carlo simulations for drilling of the different section lengths for the different wells.



ROP Data (m/hr)	P90	P50	P10
36" Open Hole:	3.58	9.15	12.63
9 7/8 Pilot Hole:	27.75	36.00	41.32
26" Open Hole:	29.00	29.00	29.00
17 1/2" Open Hole:	14.10	33.57	47.72
12 1/4" Open Hole	27.90	40.60	58.90
8 1/2" Open Hole (No Coring):	9.32	18.40	31.76
8 1/2" Open Hole (Pre-Core):	4.35	6.90	10.30
8 1/2" Open Hole (Coring):	11.84	18.33	28.00

Figure 21: Historical Timing for ROPs

List of Figures

List of Tables