Graphical Analysis of Drilling Process by Integrating Sensor Data with Reporting Meta Data

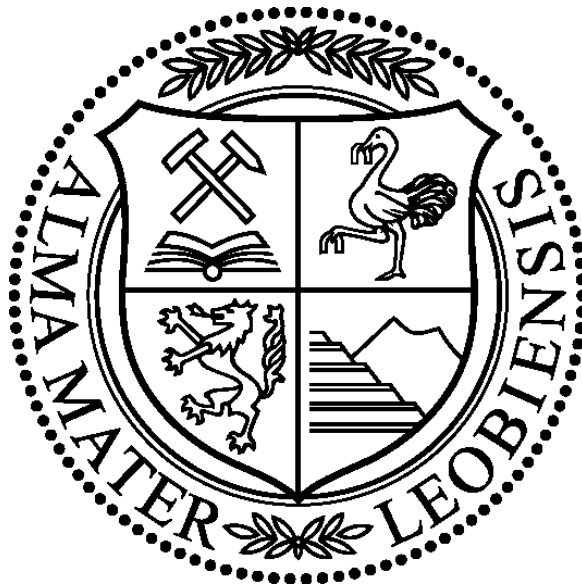*Master Thesis*

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EIDESSTATTLICHE ERKLÄRUNG

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

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

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Abstract

The main objective of oil operating companies nowadays is to increase drilling efficiency and minimize drilling cost. Thus oil companies are facing new hurdles to reduce overall cost, increase performance and reduce the probability of encountering problems. For these reasons over the last decades different methods and approaches have been introduced from different disciplines to the oil market to work towards a safe, environmental friendly and cost effective well construction. Among these approaches are software technologies which can contribute to drilling optimization and performance measurement of the drilling crews and equipment.

The purpose of this thesis is to develop a comprehensive and handy software tool which utilizes meta-data and sensor data in order to calculate the overall savings potential and indicate the potential areas of improvement.

The first part of the thesis explains about the common mechanisms of obtaining the savings potential which have been involved with this work. The savings potential could be a result of optimizing drilling operations such as drilling ahead or benchmarking the performance of the drilling crew and drilling equipment.

The second part of this work is methodology overview of the developed software tool and guideline for the new user.

The third part of this work is specified as a case study, where real data of four wells were loaded and analysed. This part also shows the beneficial use of this tool for future well planning and well time estimation. Moreover it proves the concept of drilling specific energy.

Kurzfassung

Es ist ein Hauptziel von Ölfirmen im operativen Geschäft, möglichst viele Bohrungen mit minimalen Kosten abzuteufen. Daraus ergeben sich neue Herausforderungen zur Kostenreduktion, zur Verbesserung der Bohrleistung als auch er Reduzierung der Fehleranfälligkeit betreffen.

Aus diesem Grund sind in den letzten Jahrzehnten zahlreiche unterschiedliche Methoden und Ansätze aus unterschiedlichen technischen Disziplinen entwickelt worden um sichere, umweltfreundliche und kosteneffiziente Bohrlochkonstruktionen zu ermöglichen.

Dazu gehören Software methoden, welcher zur (Arbeits-) Optimierung und Leistungsmessung bzw. Bewertung von sowohl Bohrgeräten als auch der Crew beitragen kann.

Ziel dieser Arbeit ist es ein breit anwendbares und einfach zu handhabendes Softwaretool zu entwickeln, welches Meta- und Sensordaten verwendet um Einsparungspotential zu errechnen bzw. Verbesserungspotential aufzuzeigen.

Der erste Teil der Arbeit erklärt die gebräuchlichen Mechanismen die verwendet werden, (welche auch in diese Arbeit eingeflossen sind) um Einsparungspotential zu identifizieren. Einsparungspotentiale können zum Beispiel in der Optimierung eines Bohrvorganges wie dem Bohrfortschritt in [m/t] (gebräuchlich auch: *ROP rate of penetration [m/d]*), oder auch dem Arbeitsleistungsvergleich von Crews oder auch Geräten durch Festlegung von Bezugswerten für einzelne Arbeitsschritte liegen-

Der zweite Teil der Arbeit gibt einen Überblick über die in der neu entwickelten Software verwendete Methodik, außerdem stellt er einen Leitfaden für den Benutzer dar.

Der dritten Teil ist eine Fallstudie in denen reale Bohrprozessdaten analysiert werden. Der zukünftig mögliche positive Effekt der Software auf Bohrlochkonstruktion und Zeitabschätzung wird dargelegt. Darüber hinaus beweist es das Konzept von Bohr Spezifischer-Energie.

1. Introduction

1.1. Overview

The amount of drilling data increases dramatically over the last several years. The proper analysing of the drilling data will help to increase the drilling performance and reduce the drilling operation expenditure.

Drilling performance is most of the time evaluated by comparing either the actual drilling time with planned time of a specific set of reference wells using learning curve or authorization for expenditures [AFE] with actual cost. However, there is always deviation between the actual and planned time and cost, the discrepancy between them mainly caused by non productive time [NPT]. Therefore it is necessary to analyse the NPT to identify the causes of NPT and try to avoid or mitigate them in future wells. However the other crucial source of deviation that causing NPT is ineffective drilling operations.

1.2. Challenges and Objective

Most of the existing approaches and methods which have contributed for measuring the drilling performance and determine the savings potential usually deal with one or multiples of the following parameters

- ➢ Optimizing rate of penetration [ROP].
- ➢ NPT analysis.
- ➢ Drilling cost analysis.
- ➢ Measure the performance of drilling contractors and services companies.
- ➢ Optimizing hole opening and under reaming.
- ➢ Well design optimization.
- ➢ Drilling bit selection.
- ➢ Bottom hole assembly [BHA] designing.
- ➢ Optimizing non automatically detected operations.

The differentiation between the determinations of the savings potential and non productive time is that savings potential can be identify by analysing sensor or Meta data for different operations, whereas non productive time can be only determined by Meta data. Therefore the combination of the sensor and Meta data will allow the determination of savings potential and non productive time, moreover it will help to analyse the non productive time.

The main objective of this thesis were to develop tool which utilizes meta-data and sensor data in order to calculate the overall savings potential and indicate the potential areas of improvement. Furthermore, it allows the drilling engineers to analyse and track the operations of multiple rigs and services companies, the other feature that the tool offers is it's capability to recognise the invisible lost time [ILT] from non automatically detected operations [using best composite time approach BCT].

 Figure 1 shows the working principle of the software.

The core data of the tool here is daily drilling report [DDR], it is used to identify the savings potential out of non automatically detected operation such as formation evaluation, run and cement casings and wait on cement, in addition it is used to determine the non productive time.

The other savings potential reports from different tools have been taken in to account in the developed tool, they are used to obtain the overall savings potential of the specific rig, well or phase.

Meta Data Core of the Tools Daily Drilling Report [DDR]

Optimized KOP

Final Report from ADFM

Special KPIs Target Time and BOT

Developed Software

Savings Potential from different operation analysis and optimization

Output
Multiple Charts
Total Time Analysis
Total Time Breakdown
Trouble Time Analysis
Special KPIs Tracking
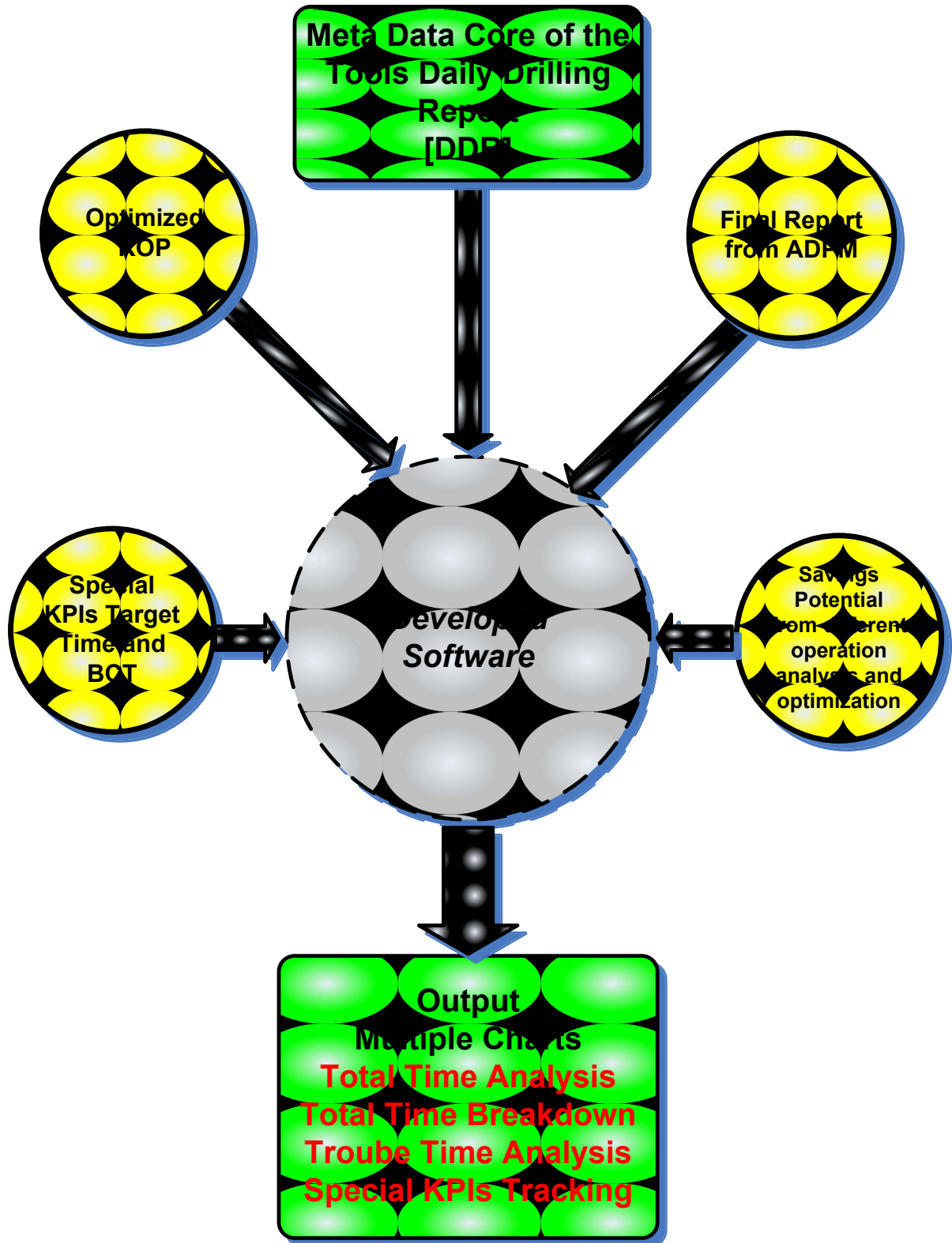
Figure 1. Working Principle of the Developed Tool

2. Special Drilling Terminologies and Drilling Activities Classification

2.1. Well Phases and Total Duration Breakdown
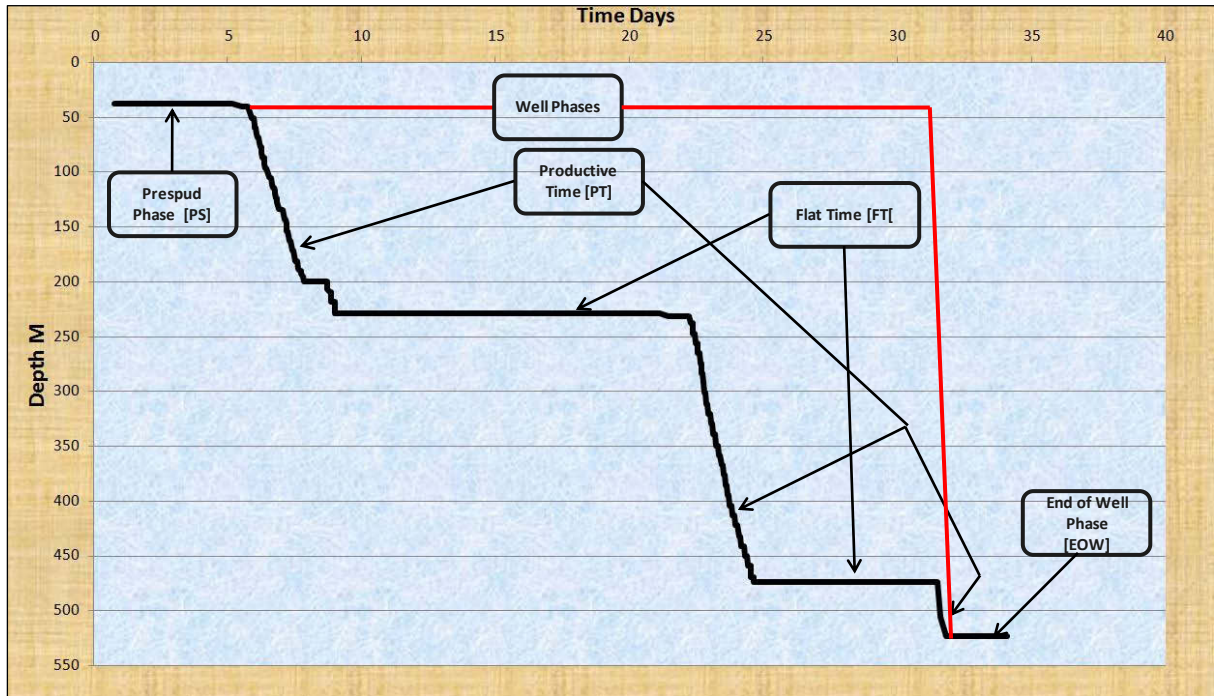
Figure 2. Major Well Phases and Total Duration Breakdown

2.1.1. Prespud Phase [PS]

Includes all operations that occurs prior to drilling the hole, examples when building up the first bottom hole assembly [BHA], mixing the spud mud.

2.1.2. Well Phases

Include all the phases between the pre-spud and end of well. The name of the well phases always related to the hole sizes. Making up BHA for drilling new formations and breaking down BHA once the total depth has been reached are the starting and ending points of a particular phase respectively.

2.1.3. Productive Time [PT]

For the sake of this master thesis the productive time is defined as the time required drill formation, whether it is sliding or rotating.

2.1.4. Flat Time [FT]

It includes all planned drilling activities that are executed excluding the ones that creates new hole. Examples of the flat time are

- Running and cement casing.
- Nipple UP/Down blowout preventer [BOP].
- Making up and breakdown BHA.
- Circulation time.
- Formation evaluation time.
- Run completion.
- Drill stem test [DST].

2.1.5. End of Well Phase [EOW]

A starting point of the end of the well phase is a company individual decision; most of the companies apply EOW once the well has reached the total depth in this case the EOW phase may include major operations such as logging, run casing, running completion, other companies use it once the well head has been installed in this case it includes only the cleaning activities.

2.2. Drilling Task Duration Classification

It is necessary, before we go further to understand the conventional classification of a total drilling task duration, the total time for any drilling task typically splits up into 3 periods, technical limit time, invisible lost time and lost time. Figure 2 presents the conventional drilling task duration classification.
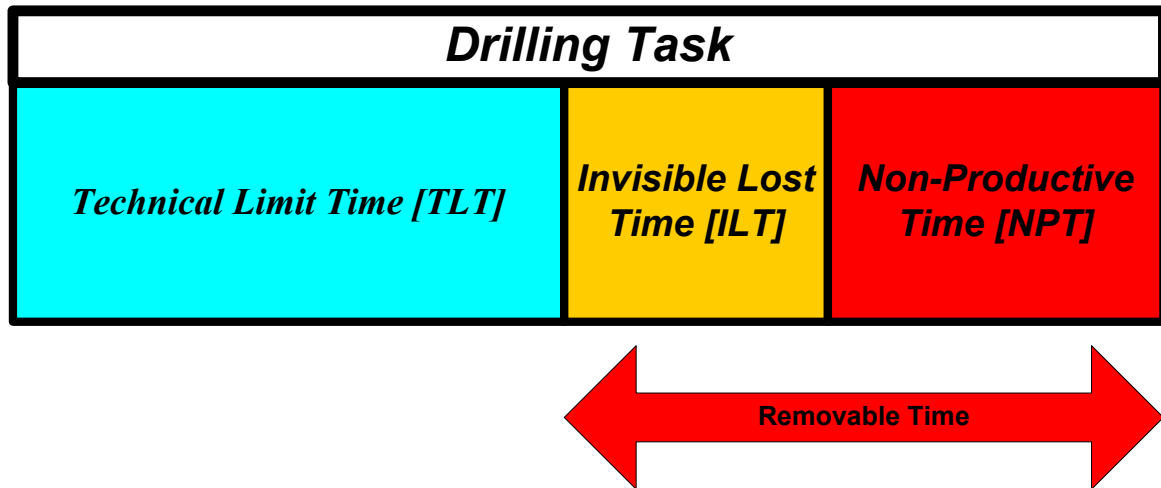
Figure 3. Conventional Drilling Task Duration Classification[2]

2.2.1. Non-Productive Time [NPT]

It is caused by human errors, tool failures or unpredicted environmental events and it will result in considerable loss of time and money. Classification of NPT is described in the following points.

Rig Equipment	Down time due to mud pumps, generators, shakers, rotary table, top drive/Kelly, hoist, drilling line, gauges, compressors, anchors.
Surface Equipment	Downtime in this category includes Surface and Sub-sea equipment including wellheads, BOPs and control equipment, riser, rig floor equipment [tongs, iron roughneck], wear bushing setting problems. Leaks on wellhead and BOPS.
Down-hole Equipment	Downtime here includes measuring while drilling [MWD], BHA elements such as adjustable stabilizer, hole opener.

Drill string Equipment	Includes: twist offs, wash-outs, backed-off strings, plugged pipes, collapsed pipes, plugged bit and bit failure.
Stuck Pipe	Down time is recorded from the moment the string is considered stuck to the point where it is released and operations are back to before the stuck time.
Logging Equipment	This is the time lost during formation evaluation. This includes downtime due to failure of logging while drilling [LWD] tools, wireline tools, stuck logging tools, failure of surface related equipment including wireline reels, electrical faults.
Fishing	Time spent on fishing such as BHA elements or drill string even wireline tools.
Fluids	Time lost due to the need to condition mud properties, shortage of mud materials , mixing of mud.
Hole Problem	This includes lost circulation, wellbore instability and hole collapse. Tight hole problems resulting in changes in BHA configuration, POH and RIH of new string.
Well Control	Time lost from the moment the kick is detected and BOPS operated to the time when operations are back to the moment before the kick.
Testing &Completion	This includes all NPT related to running the completion and well testing.

2.2.2. Invisible Lost Time ILT

This time is usually absorbed in both productive and flat time; it is defined as the difference in time between the actual operation duration and the best practice time. It can be recognised only by optimizing the drilling operations or benchmarking the performances of drilling crew and equipment.

2.2.3. Technical Limit Time TLT

It is the possible theoretical time required to finish a specific drilling operation within the planned frame. However it is not easy to estimate the technical limit time for every single drilling operation.

In order to estimate and plan the TLT we have to first answer the following questions,

- Where are we now? Current performance.
- What is the possible? Theoretical limit.
- How do we get there? New technology tools.

Once we have the proper answers for the mentioned questions then we move forward to the processing steps, here we should be able to

- Identify current performance in term of time for individual tasks.
- Define the best practical ever time for every individual task. Technical limit.
- Plan for removing the gap between the current performance and technical limit in the future wells.

2.3. Data classification and characterization

The term data refers to qualitative or quantitative attributes of a variable or set of variables. Data are typically the results of measurements and can be the basis of graphs, images, or observations of a set of variables. In drilling operations there are two kinds of data, metadata and sensor data.

2.3.1. Sensor Data

A sensor measures the physical conditions of the drilling parameters such as pressures, flow rate, hook load etc, these physical measuring then they converted to digital numeric values that can be manipulated by a computer this process called data acquisition.

The components of the data acquisition system include

- Sensors that convert physical parameters to electrical signals.
- Signal conditioning circuitry to convert sensor signals into a form that can be converted to digital values.
- Analogy-to-digital [A/D] converters, which convert conditioned sensor signals to digital values

 Figure 4 shows the sequences of processing the sensor data whereas Table 1 depicts an example of surface rig sensors output in form of digital values.
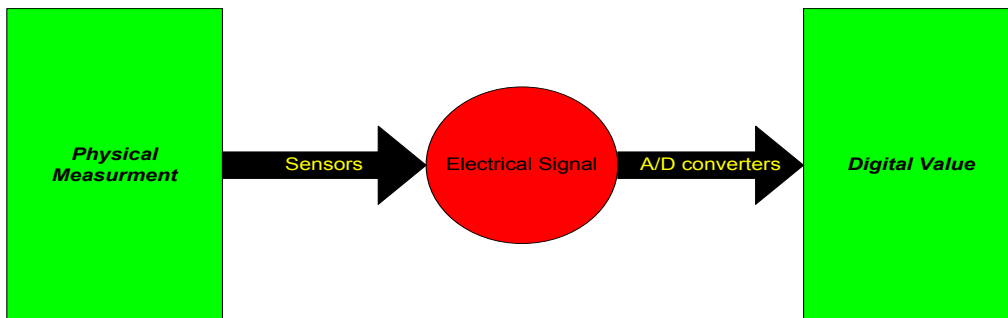
Figure 4. Sequences of Processing the Sensors Data

Data	Time	Tot Depth	Bit Depth	ROP	ROP ft/hr	HK Hght	WOH hy	WOB	RPM	TORQUE	SPP	FLWpmps	MWIN	T Revol	Pump Time
		ft	ft	mn/ft	ft/hr	ft	klbs	klbs	rpm	lb*ft	psi	gpm	ppg	krev	h
07-Nov-10	0:00:10	9273.3	9273.3	1.9	30.8	32.7	279.6	13.1	179	7882	3084	761	10.3	28	3.9
07-Nov-10	0:00:20	9273.3	9273.3	1.9	30.8	32.7	281	11.6	179	8236	3114	759	10.3	28	3.9
07-Nov-10	0:00:30	9273.5	9273.5	1.9	30.8	32.6	281.4	11.2	180	8021	3107	759	10.3	28	3.9
07-Nov-10	0:00:40	9273.6	9273.6	1.8	32.4	32.5	281.1	11.5	179	8649	3118	760	10.2	28	3.9
07-Nov-10	0:00:50	9273.7	9273.7	1.8	32.4	32.4	280.4	12.2	179	8629	3120	759	10.2	28	3.91
07-Nov-10	0:01:00	9273.7	9273.7	1.8	32.4	32.4	279.5	13.2	180	8883	3126	758	10.2	28	3.91
07-Nov-10	0:01:10	9273.7	9273.7	1.8	32.4	32.3	280.9	11.8	179	7984	3120	758	10.3	28	3.91
07-Nov-10	0:01:20	9273.8	9273.8	1.8	32.4	32.2	281.5	11.1	179	8178	3101	758	10.3	28	3.91
07-Nov-10	0:01:30	9273.9	9273.9	1.8	32.4	32.1	280.7	12	179	7868	3119	760	10.3	28	3.92
07-Nov-10	0:01:40	9274	9274	1.8	32.4	32	280.1	12.5	180	8996	3137	761	10.3	28	3.92
07-Nov-10	0:01:50	9274.1	9274.1	2.3	26.1	32	281.2	11.4	180	8272	3139	760	10.3	28	3.92
07-Nov-10	0:02:00	9274.2	9274.2	2.3	26.1	31.9	281.3	11.3	180	8680	3133	760	10.3	28	3.93
07-Nov-10	0:02:10	9274.3	9274.3	2.3	26.1	31.8	279.8	12.8	179	8010	3120	761	10.3	28	3.93
07-Nov-10	0:02:20	9274.3	9274.3	2.3	26.1	31.8	279.9	12.7	180	8587	3095	761	10.2	28	3.93
07-Nov-10	0:02:30	9274.4	9274.4	2.3	26.1	31.7	281.4	11.2	179	7904	3123	758	10.3	28	3.93
07-Nov-10	0:02:40	9274.5	9274.5	2.3	26.1	31.6	281.4	11.2	179	7112	3088	760	10.3	28	3.94
07-Nov-10	0:02:50	9274.6	9274.6	2.1	28.4	31.5	280.3	12.4	179	7507	3118	761	10.2	28	3.94
07-Nov-10	0:03:00	9274.6	9274.6	2.1	28.4	31.5	279.8	12.8	179	7613	3105	759	10.2	28	3.94
07-Nov-10	0:03:10	9274.6	9274.6	2.1	28.4	31.4	280.3	12.3	180	8344	3106	761	10.2	29	3.95
07-Nov-10	0:03:20	9274.7	9274.7	2.1	28.4	31.4	282.1	10.5	180	7569	3115	761	10.3	29	3.95
07-Nov-10	0:03:30	9274.8	9274.8	2.1	28.4	31.2	281.1	11.5	179	7803	3127	760	10.3	29	3.95
07-Nov-10	0:03:40	9274.9	9274.9	2.1	28.4	31.1	280.6	12	180	8473	3131	762	10.3	29	3.95
07-Nov-10	0:03:50	9275	9275	2.1	28.4	31.1	279.9	12.7	180	8417	3152	764	10.3	29	3.96
07-Nov-10	0:04:00	9275	9275	2.1	28.4	31.1	281.1	11.5	180	7101	3167	763	10.3	29	3.96
07-Nov-10	0:04:10	9275.1	9275.1	2.4	24.5	30.9	281.6	11	180	7019	3133	763	10.3	29	3.96
07-Nov-10	0:04:20	9275.2	9275.2	2.4	24.5	30.9	280.3	12.3	180	8055	3153	764	10.3	29	3.96
07-Nov-10	0:04:30	9275.2	9275.2	2.4	24.5	30.9	279.5	13.1	181	7268	3157	768	10.3	29	3.97
07-Nov-10	0:04:40	9275.3	9275.3	2.4	24.5	30.8	281.8	10.8	181	7534	3153	770	10.3	29	3.97
07-Nov-10	0:04:50	9275.4	9275.4	2.4	24.5	30.7	281.4	11.2	181	7415	3142	771	10.3	29	3.97
07-Nov-10	0:05:00	9275.5	9275.5	2.4	24.5	30.6	281	11.6	182	7913	3158	772	10.3	29	3.98
07-Nov-10	0:05:10	9275.5	9275.5	2.1	28.7	30.5	280.3	12.3	181	7932	3222	773	10.3	29	3.98
07-Nov-10	0:05:20	9275.6	9275.6	2.1	28.7	30.5	280	12.6	182	7339	3204	775	10.3	29	3.98
07-Nov-10	0:05:30	9275.6	9275.6	2.1	28.7	30.4	281.5	11.1	181	6927	3181	772	10.2	29	3.98
07-Nov-10	0:05:40	9275.7	9275.7	2.1	28.7	30.3	282	10.6	182	7512	3180	772	10.2	29	3.99
07-Nov-10	0:05:50	9275.9	9275.9	2.1	28.7	30.2	281.4	11.2	181	7668	3157	772	10.2	29	3.99
07-Nov-10	0:06:00	9275.9	9275.9	2.1	28.7	30.1	280.4	12.2	182	7600	3160	774	10.2	29	3.99
07-Nov-10	0:06:10	9276	9276	2.1	28.7	30.1	280.1	12.5	181	8246	3129	773	10.3	29	4
07-Nov-10	0:06:20	9276.1	9276.1	2.4	24.7	30	281.3	11.3	182	8222	3163	775	10.3	29	4

Table 1. An Example of Surface Rig Sensors out put in Form of Digital Values

2.3.2. Metadata

Metadata is structured information that describes, explains, locates, or otherwise makes it easier to retrieve, use, or manage an information resource. Metadata is often called data about data or information about information[3].

There are three main types of metadata:

- ➢ Descriptive metadata
- ➢ Structural metadata
- ➢ Administrative metadata
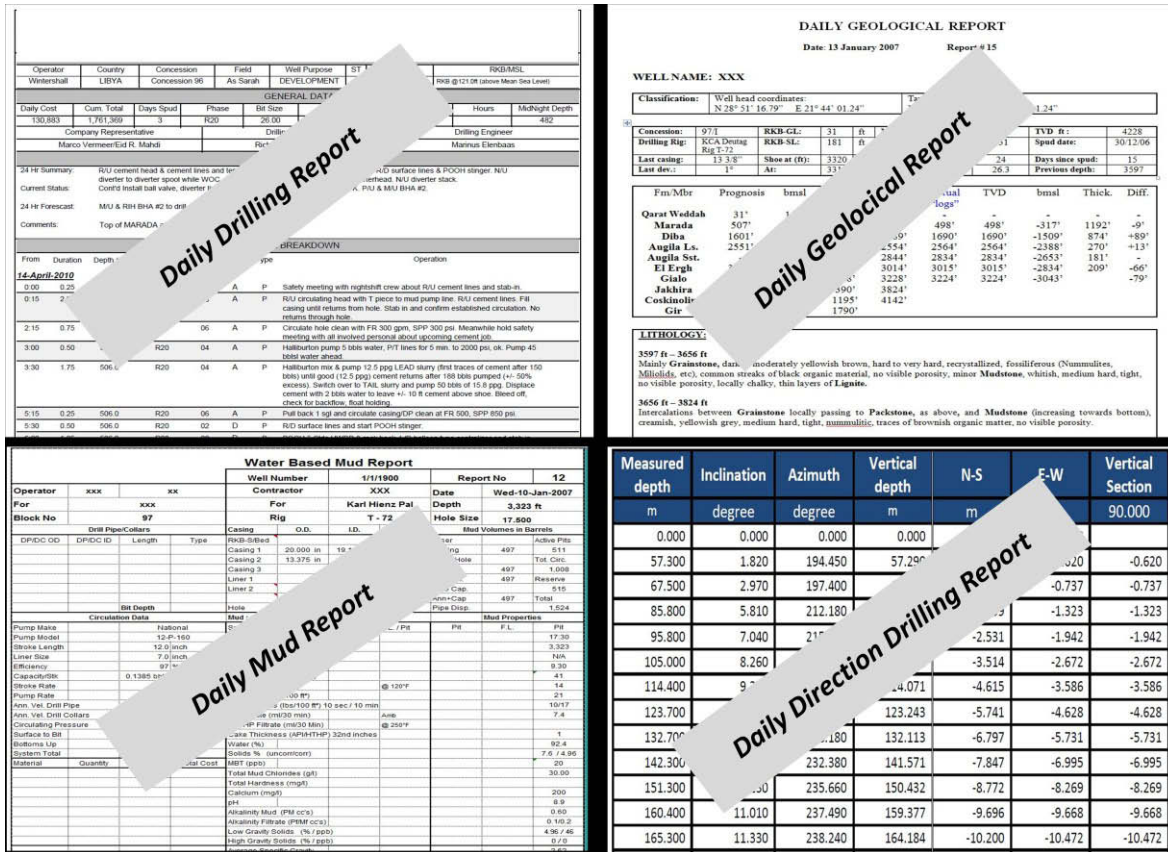
Figure 5. Common Daily Generated Metadata in the Rigs

2.4. Drilling Activities Classification

There are three essential reasons for classification and coding of the drilling operations, first drilling statistic and analysis, second drilling time and cost estimate, finally drilling performance review. Drilling activities classification system may use different levels of codes the example of the system with five levels is given below[1].

- Phase Codes

- Class Codes

- Major Operation Codes

- Operation Codes

- Trouble Codes

Appendix A describes in details the drilling activities classification system which is recognized by the developed tool.

3. Methods to Obtain Savings Potential Time

3.1. Savings Potential

In drilling savings potential time is the time which can be identified when

- o Optimizing specific drilling operations such as rate of penetration.
- o Benchmark surface routine drilling operations.
- o Manipulating best composite time for non automated detected operations such as wellhead work.
- o Non productive time is usually considered to be saving potential if it could be eliminated or mitigated in future wells.

3.1.1. Drilling Optimization

Drilling optimization is a process that manipulates down-hole data and surface sensors data, computer software, Measurement-While- Drilling (MWD), and experienced expert personnel all dedicated to reduce trouble time and increase drilling efficiency.

Most of the drilling operations can be optimized. However, within the context of this work the optimization of rate of penetration solely will be explained.

3.1.2. Performance Measurement of Crews and Drilling Equipment

By utilizing mud logging data it became possible to measure and compare the performance of drilling crews and equipment. The mentioned performance here means the daily routine job of the drilling crews such as making up or break down bottom hole assembly BHA, trip in , trip out, making slip to slip connection, running the completion, run riser and running casing..Etc.

Automated drilling performance measurement [ADPM] is commercial software on the market which can identify the savings potential by analyzing and benchmarking particular key performance indicators that connected directly to the routine drilling operations of

the drilling crews and equipments. The process of obtaining the savings potential by ADPM will be explained in details in this chapter.

3.1.3. Non Automatically Detected Operations

It is well known that if we can measure an operation then we will be able to optimize, improve and benchmark it, however not all drilling operations can be measured. Therefore the best way to improve and evaluate such non automatically detected operation is to compare it with similar operations and identify the best composite time.

3.2. Optimizing Drilling Rate of Penetration with Drilling Specific Energy

3.2.1. Rate of Penetration definition and types

Rate of penetration [ROP] is defined as the ratio of the total length drilled to the advancement in unit time. There are two kinds of ROP which can be measured while drilling is still in progress, instantaneous ROP and average ROP[4].

Instantaneous ROP

It is measured over a finite time or distance; it reflects the function of the instantaneous drilling system under specific operational conditions.

Average ROP

It is measured over the total interval drilled; it can be phase ROP, job ROP or Run ROP.

Measuring ROP

ROP is distance unit divided by time unit. Hook position indicator is a simple device that indicates how high the hook is above the rotary table, as the drilling is in progress the hook is increasingly lowered to compensate for the new hole made, by counting the time required for hook to move from one depth to another, the ROP can be calculated.

3.2.2. Factors Affecting Rate of Penetration

The factors which influence ROP can be classified under two categories, controllable and environmental. Controllable factors are the factors that can be promptly changed, whereas environmental factors are unpredictable and uncontrollable such as formation properties. Table 2 shows the controllable factors which have an effect on the ROP.

Weight on Bit [WOB]	Bit Rotating Speed [RPM]	Bit Nozzle Size	Flow Rate
Mud Weight	Mud Rheology	Bit Performance [HSI]	Bottom Hole assembly design

Table 2. Controllable Factors Which Have an Effect on the ROP[5]

3.2.3. Concept of Mechanical Specific Energy

3.2.3.1. History

Mechanical Specific Energy (MSE) is not a new idea; it has been used to achieve the maximum drilling performance. MSE is defined as the amount of energy required to destroy a unit volume of rock.

Teale proposed the following equations for calculating the MSE[6],

$$MSE = \frac{WOB}{Ab} + \frac{120 * \pi * RPM * TOB}{Ab * ROP} \qquad \text{Eq 1}$$

In order to calculate the MSE by using Eq 1, we have to have the torque on bit [TOB]. Bit torque [TOB] is easy to measure with Measuring While Drilling [MWD] tool. However MWD is not always in use , since it is expensive and not required special in vertical wells, therefore in order to obtain the bit torque when it is not available Pessier and Fear introduced a bit specific coefficient of sliding friction μ, it links the torque on bit with weight on bit subsequently TOB can be calculated[7].

$$\mu = 36 * \frac{TOB}{Db * WOB}$$ Eq 2

$$TOB = \frac{\mu * Db * WOB}{36}$$ Eq 3

The field applications for specific coefficient of sliding friction are 0.25 and 0.5 for tricone and PDC bit respectively.

By substituting TOB in Eq 1 by Eq 3, the final equation of the MSE will be,

$$MSE = \frac{WOB}{Ab} + \frac{13.33 * \pi * RPM * WOB}{Db * ROP}$$ Eq 4

Teale also introduced a equation that calculate the mechanical efficiency, the maximum efficiency can be reached only when the MSE equal to unconfined compressive strength of the rock [UCS].

$$Mechanical\ Efficiency = \frac{UCS}{MSE} * 100$$ Eq 5

3.2.3.2.   Potential Benefits of Surveillance of the Mechanical Specific Energy

- ➢ Sustaining optimal drilling parameters for the life of the bit.
- ➢ Monitoring drilling efficiency, indicated by rapid increase of MSE.
- ➢ Increasing ROP to the maximum regardless of the bit type.
- ➢ Knowing when to replace a bit when performance is suboptimal.
- ➢ Identify drilling dysfunctions.
- ➢ Could indicate bad hole quality.
- ➢ Help to assess the under-reamer and bit dull state.

3.2.3.3.   Drilling Specific Energy versus Rate of Penetration

Drilling specific energy [DSE] is the energy required to destroy a unit of rock volume and remove it up. The initial MSF equation was modified by involving a new term into the equation; this term is the bit hydraulic. DSE can be calculated as follow[8]:

$$DSE = \frac{WOB}{Ab} + \frac{13.33 * \pi * RPM * WOB}{Db * ROP} - \frac{1980000 * \text{Λ} * \text{hpb}}{ROP * Ab}$$ Eq 6

Λ is the bit hydraulic factor, it is depends on the bit diameter.
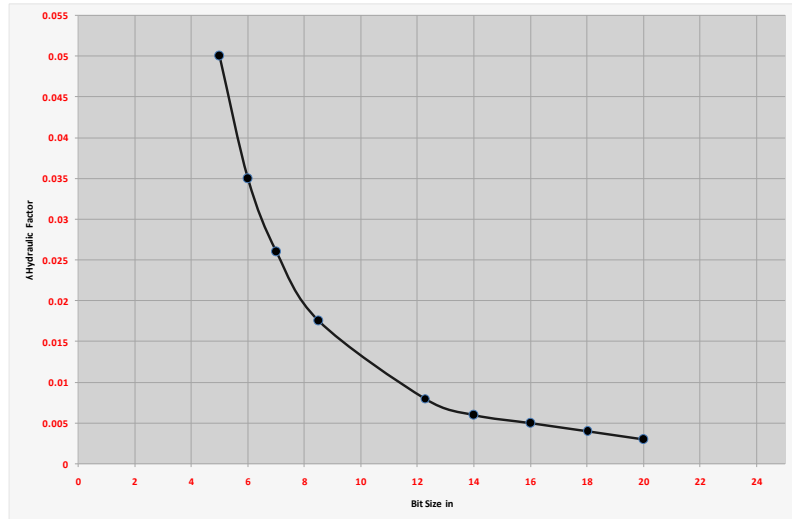
Figure 6. Bit Hydraulic Factor Λ and Bit Size[8]

A lot of comprehensive studies were performed in order to realize the real relation between the ROP and MSE, the results always show the strong link between both of them, back to Eq 6 we can see that the factors which are involved to calculate the DSE are the same factors which affect the ROP.

The conventional method to determine the optimum ROP is drill off test. It is the test which combines the weight on bit with rotary speed in order to maximize the ROP and determine founder Point. The founder point is defined as the point at which ROP stops responding linearly with increasing WOB and RPM .There are two methods to perform the drill off test, active and passive. The following paragraphs explain the steps of performing the both kind of drill of test.

Active Drill of Test

- o Select minimum recommended WOB and moderate RPM [it can be found at the bit specification book].
- o Maintain initially selected WOB by replacing it as drilling occurs and record average ROP.

- o Increase WOB dramatically, continuing to record average ROP.

- o Continue until ROP no longer increases.

- o Repeat steps 1-4 using different RPM's.

- o Plot data WOB vs. ROP and select the weight and RPM combination which provide the highest ROP.

Passive Drill of Test

- o Select the WOB to start the test that presents 80% of maximum bit weight range, as specified by manufacture.

- o While bit is off bottom, select proper RPM, usually above the recommended.

- o Lock the break down and record the time elapsed to drill off [2000 or 5000 lbf increments]. Do not add any weight to the bit during the test. Allow the bit to drill until no further drill off can be noticed.

- o Incrementally increase and decrease rotary speed from initially selected rotary speed and repeat steps 1-3.

- o Compare the data and select the weight increment and rotary speed requiring the least amount of time to drill off.

If we connect between the traditional plot of ROP versus WOB with DSE versus ROP, from first glance we can realize the connections between them, in both plots there are three different zones,

- o Zone one presents inefficient drilling.

- o Zone two is the optimal drilling.

- o Zone three is the transition zone between zone one and two.

 Figure 7 shows the traditional ROP versus WOB plot and the three zones whereas Figure 8 depicts the relation between DSE and ROP and the three zones.
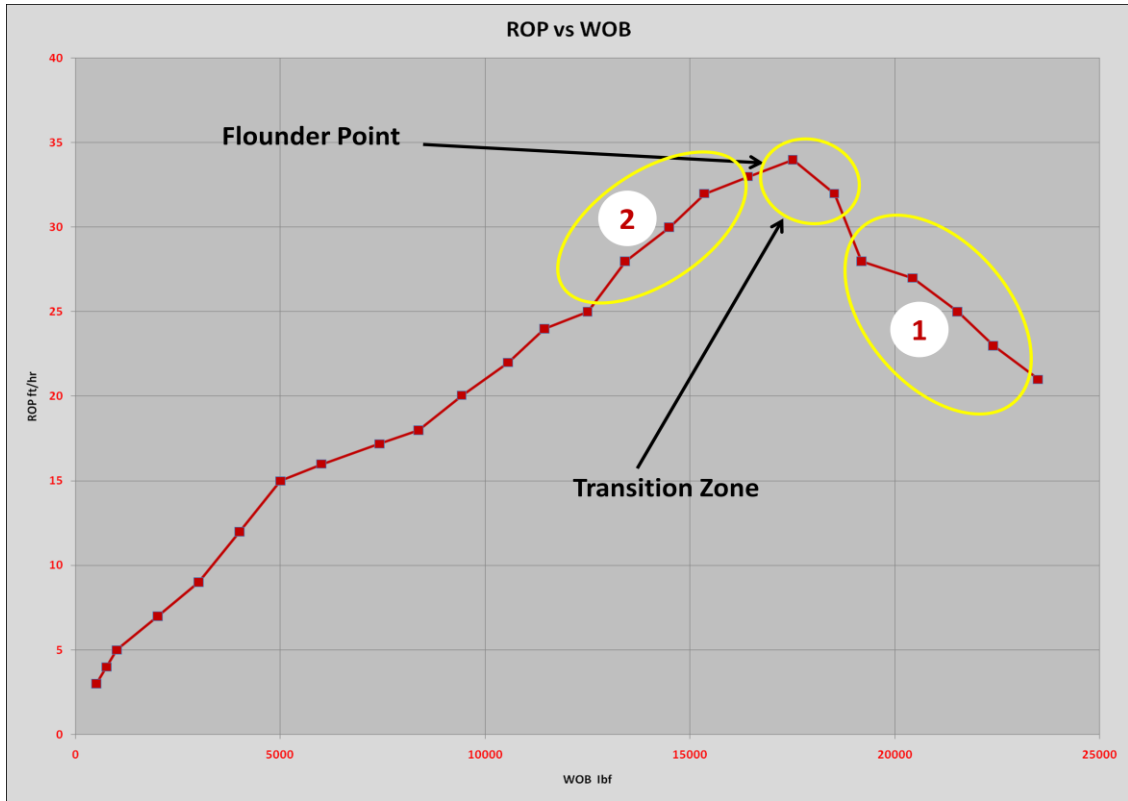
Figure 7. ROP versus WOB Plot[8]
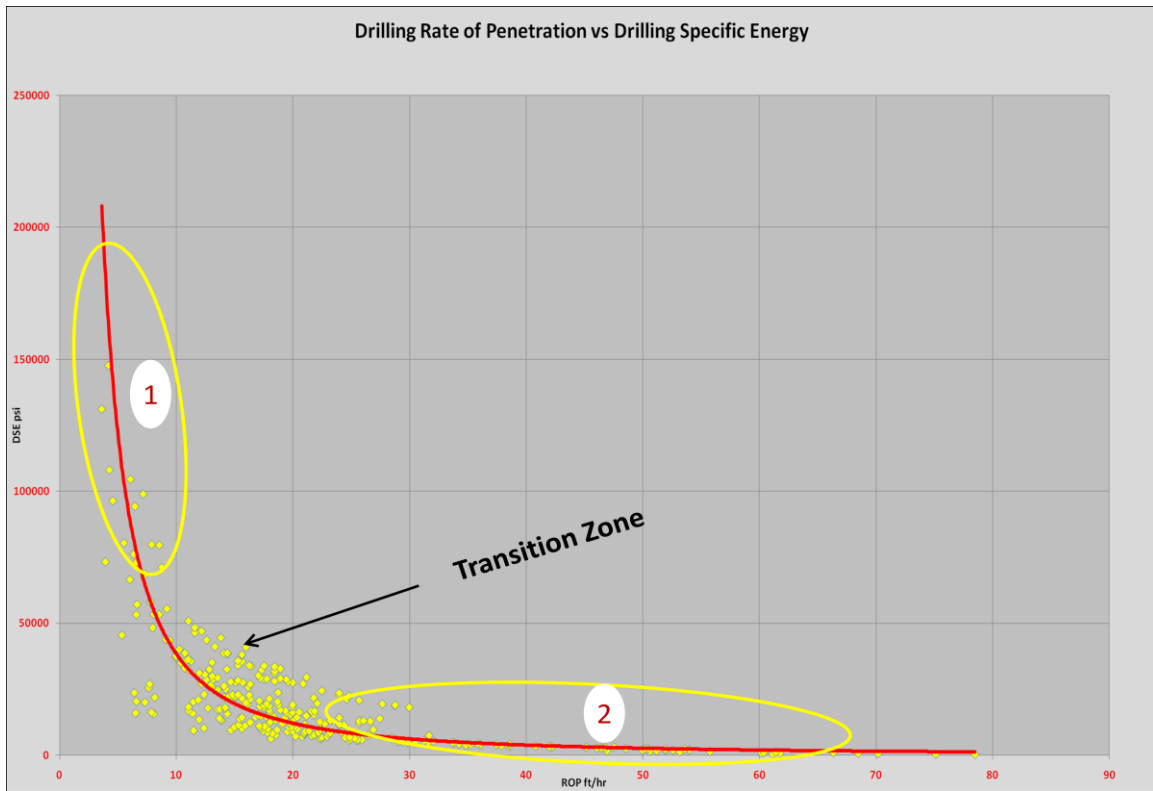
Figure 8. DSE versus ROP[8]

As it is mentioned the drill of test determines the flounder point by controlling two parameters, it will be valid only for the specific condition, whereas real time monitoring of DSE observing and combining the entire factors which influence the instantaneous ROP.

3.3. Concept of Probability Distribution

As it was pointed out real time specific energy monitoring and optimization lead to increase the drilling efficiency by increasing ROP. However, this approach does not work when analyzing historical data. Therefore and for the context of this thesis probability distribution approach for determining the optimal theoretical ROP will be explained. It is used in the case study to obtain the optimal ROPs for different phases, which then were loaded into the developed tool in order to calculate the savings potential.

The probability is always linked to the risk analysis and uncertainly. However, the probability which is described here does not refer to the risk since it is related to the historical data. The probability density function shows the statistical distributions of the historical ROPs.

3.3.1. Probability Distributions

A large amount of probability distributions exist, they have been designed to fit special purposes. The probability distributions can be discrete or continuous depending on the nature of the variable. Binormial, Poisson and Multinomial are called discrete distributions whereas normal, lognormal and triangular are continuous distribution examples.

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

The probability of any variable that is presented in the cumulative density function graphic is determined by calculating the area in the left side of the interested variable under the curve in the probability density function graphic[9].
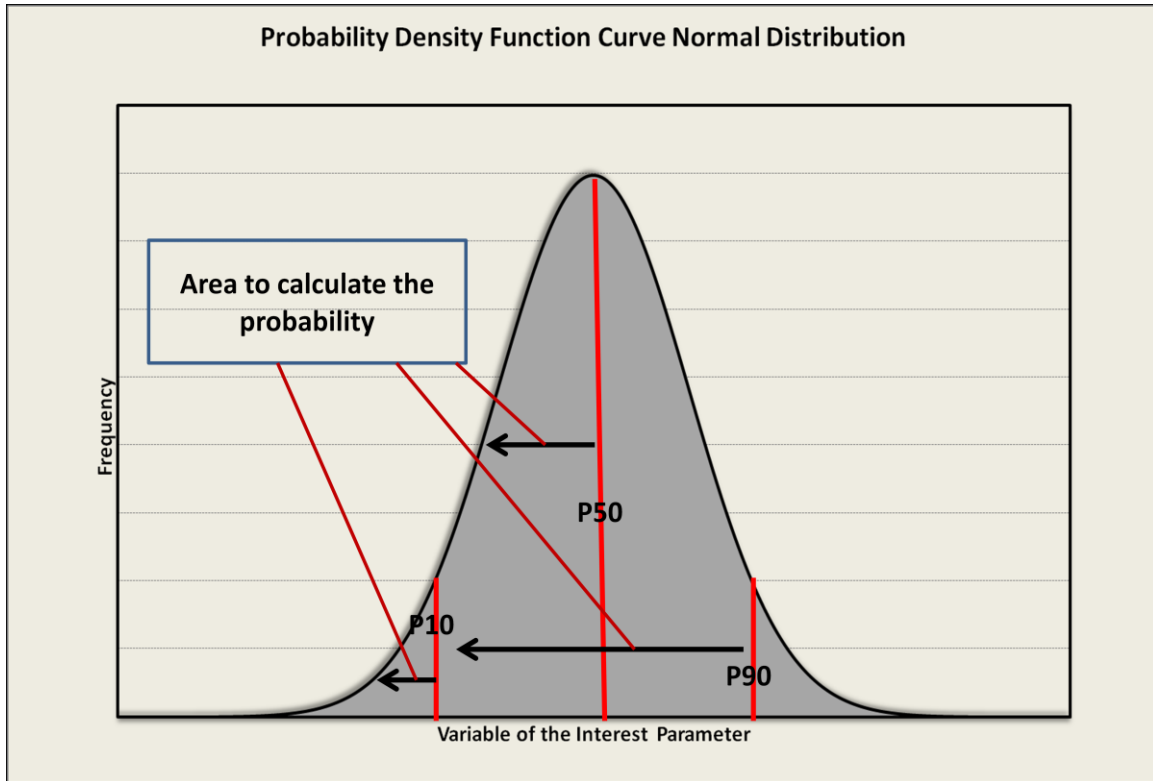
Figure 9. An Example of Normal Probability Density Function
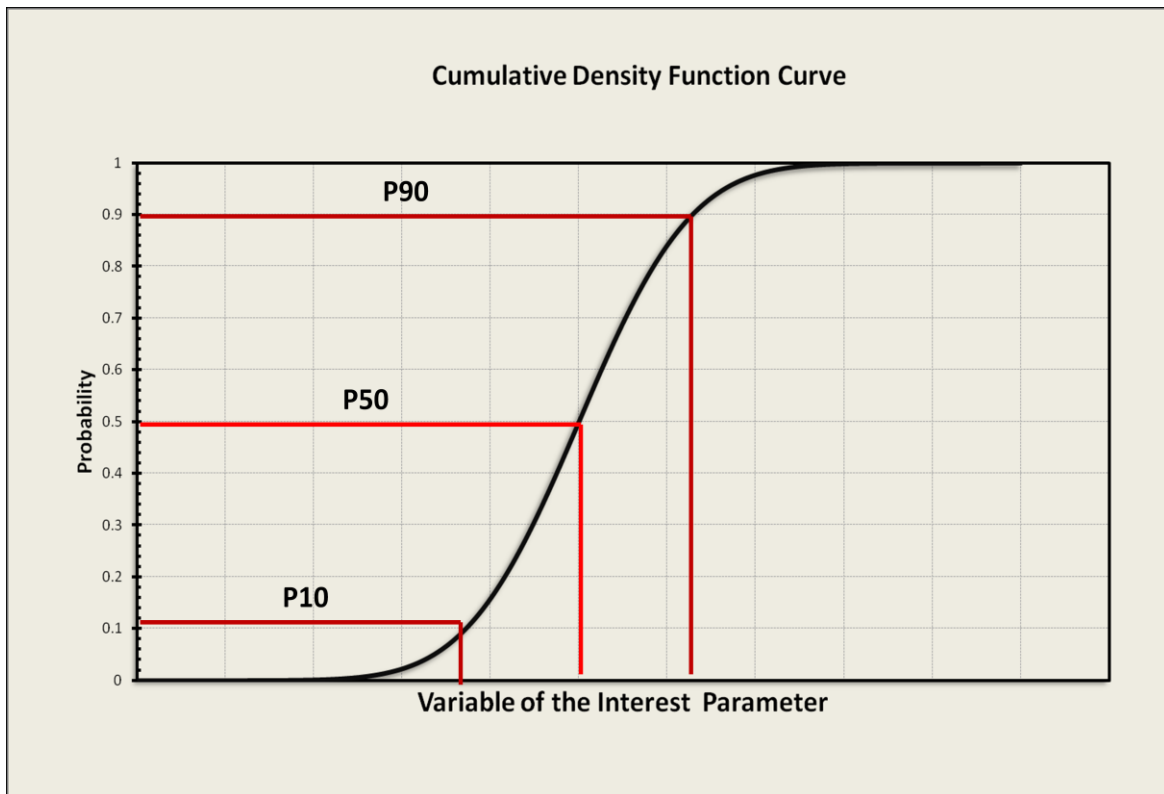
Figure 10. An Example of Cumulative Density Function

P10

It is the probability which is likely to be met 90% of the time. It is widely used in the oil industry and it gives the accurate and reliable estimate.

P50

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

P90

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

Figure 11. Comparison between the Probability Distributions of the Current and Enhanced ROPs

The probability distribution can be a contributing factor to improve the ROPs in future wells .Plotting the probability distribution of the current ROPs helps to identify the new

target and by looking to the main factors which can enhance the ROP the selected target can be achieved in the future.

In general the improvement process in this case can be summarized as following,

- Plot the probability distribution of the current ROP.
- Identify the target [In the case study the target is P50]
- Find the way to reach the selected target in future wells [In the case study the concept of DSE was used to identify the factors which caused the low ROP.

3.4. Automated Drilling Performance Measurement of Drilling Crews and Equipment

In order to evaluate and measure the performance of drilling crews and equipment that contribute to drilling operations we must identify special key performance indicators that can be measured and benchmarked.

Automated Drilling Performance Measurement ADPM is the tools which is able to detect and classify the routine drilling operations. Moreover it calculates special predefined key performance indicators in order to identify savings potential by analyzing and benchmarking the detected KPIs that can be produced by drilling crews or equipment.

3.4.1. Detection of Routine Drilling Operations

ADPM combines two sources of data in order to classify the drilling operations, the surface sensors data and daily drilling report data. However detection of drilling operations required just the surface sensors data. Classification of the drilling operation based on the morning report is used in the later stage to link specific operations to the right predefined KPIs.The examples of drilling operation detection are illustrated in Figure 12 and 13, whereas Figure 14 and 15 show the operation classification examples.
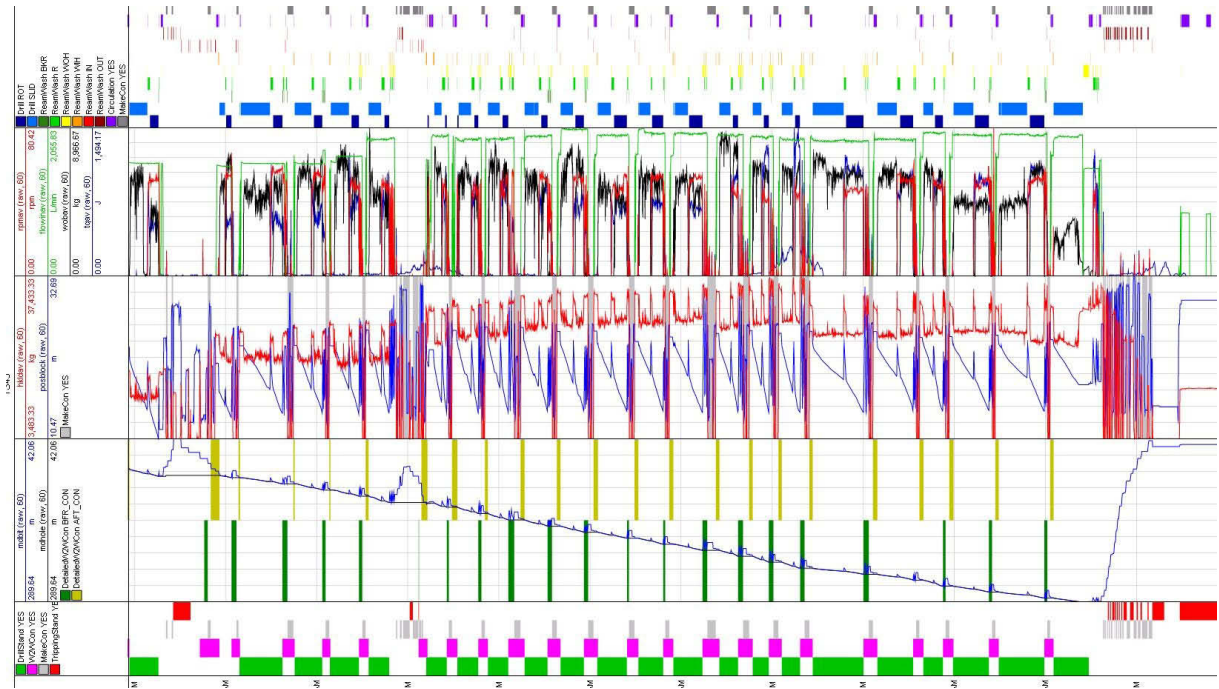
Figure 12. Automated Drilling Performance Measurement ADPM Drilling Operation Detection Example 01
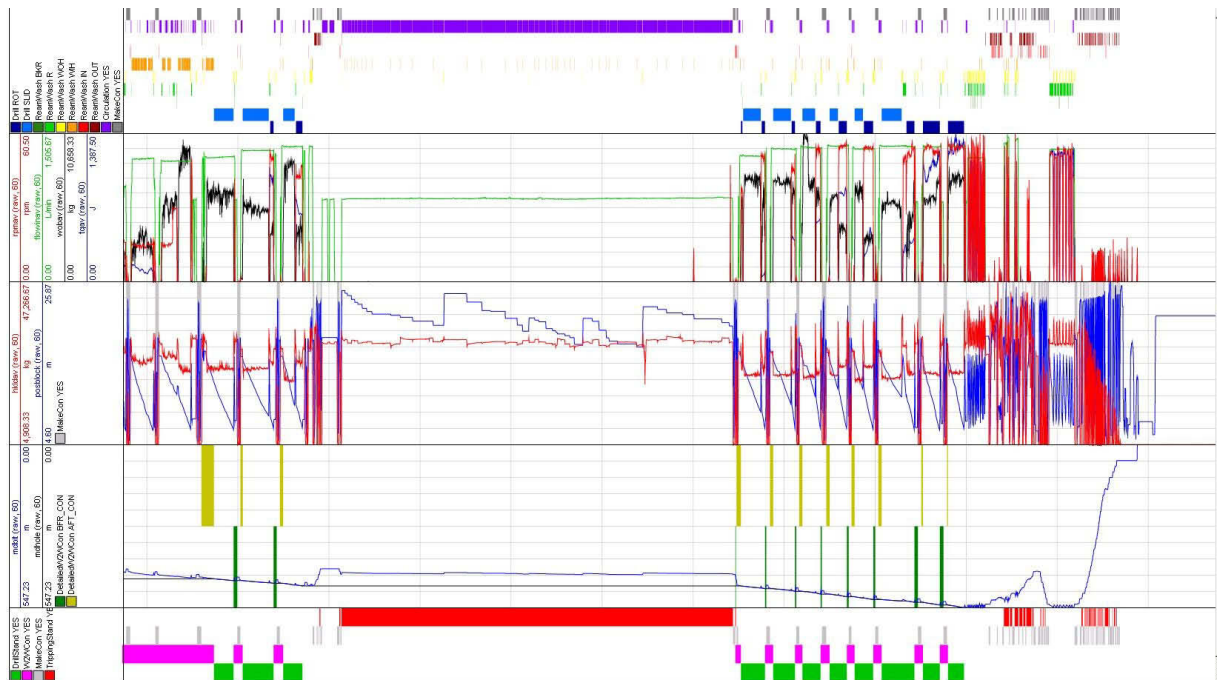
Figure 13. Automated Drilling Performance Measurement ADPM Drilling Operation Detection Example 02
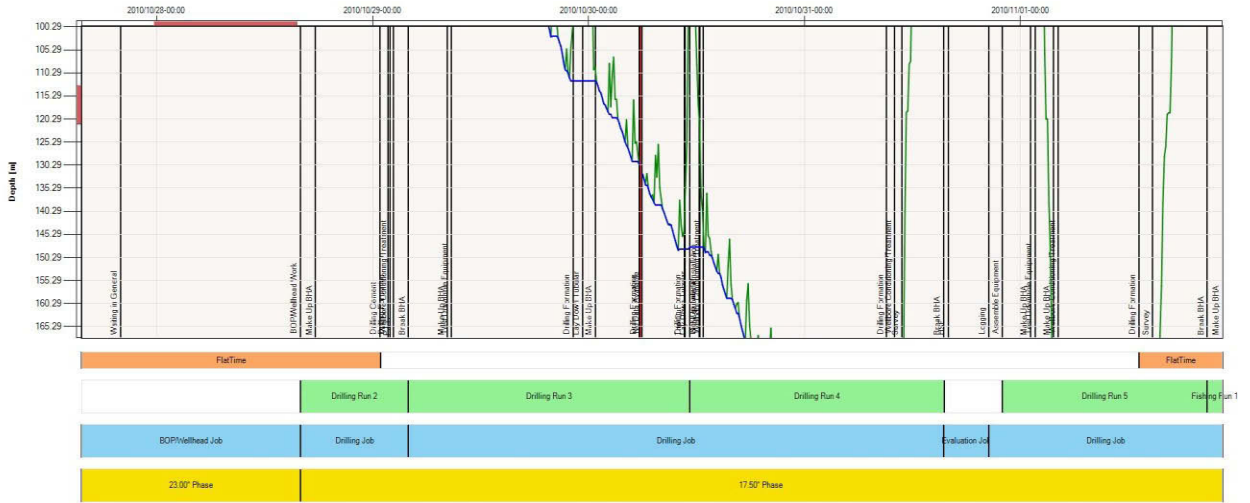
Figure 14. Automated Drilling Performance Measurement ADPM Drilling Operation
Classification Example 01
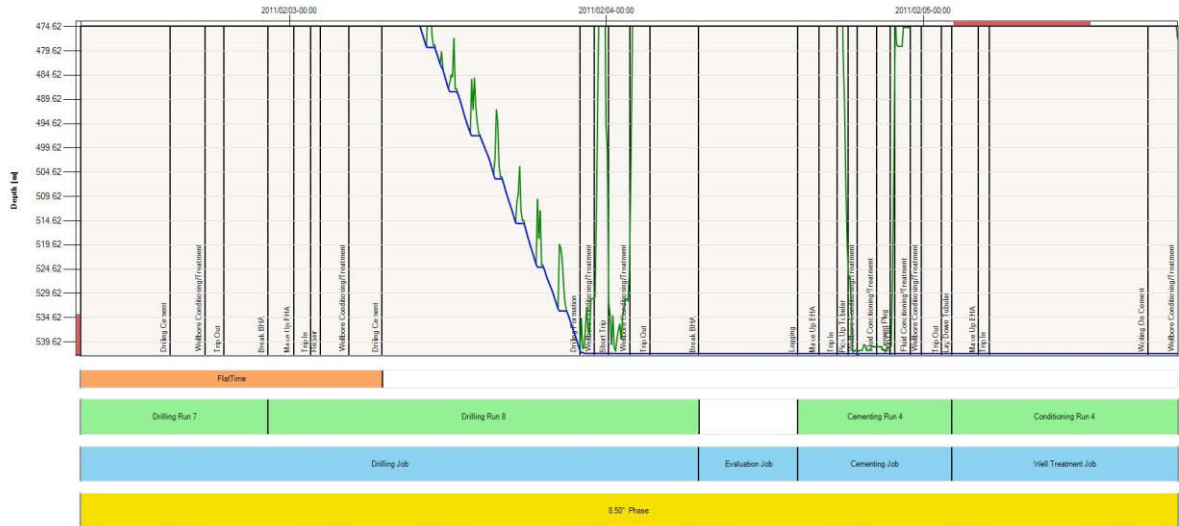
Figure 15. Automated Drilling Performance Measurement ADPM Drilling Operation
Classification Example 02

3.4.2. Key Performance indicators [KPIs]

The ADPM tool calculates numerous KPIs and sorts them under different categories, in this
section only KPIs which are involved in the developed software will be explained in details,
the list of other KPIs can be found in Appendix B.

3.4.2.1.   KPIs Related to Tripping

Tripping Slip to Slip Connection Time is the time spent in slips and making a connection during tripping operations. This KPI is also available separately for the running (RIH) and pulling (POOH) part of the run.

Tripping Pipe Moving Time represents the time needed for running one stand of drill pipe in or out of the hole. Actually it is the time between two slip to slip connections.

3.4.2.2.   KIPs Related to Running BHA

BHA Slip to Slip Connection Time is the time spent in slips during running BHA. This KPI is also available separately for the running (RIH) and pulling (POOH) part of the run.

BHA Pipe Moving Time is the time needed for running one stand of BHA into and/or out of the hole. Actually it is the time between two BHA slip to slip connections.

3.4.2.3.   KPIs Related to Drilling

Drilling Weight to Weight Time represents the time between two drilled stands. This KPI starts when the drill string is lifted off from bottom and lasts until the string is on bottom drilling again. This operation includes all wellbore conditioning as well as the drilling slip to slip connection conducted during this interval.

Drilling Wellbore Treatment Time per Stand is time spent on wellbore treatment (ream up/down, wash up/down and circulation) during drilling one stand of pipe excluding the weight to weight connection period for that stand.

3.4.2.4.   KPIs Related to Running of Casing and Tubing

Slip to Slip Connection Time is the time spent in slips during running casing and/or tubing (excluding the drill pipe).

Pipe Moving Time represents the time needed for running one joint of casing/tubing into the hole. Actually it is the time between two casing/liner slip to slip connections.

3.4.3. Recognition of the Invisible Lost Time

Analyzing data always preferred to be in visual manner thus ADPM generates a set of histogram plots .Those histogram plots can be used to analyze any KPI at any level and time interval. Moreover they provide the user with significant information about the selected KPI such as the operations count, P10, P50 and P90.

 In addition they give indications about the consistency of crew performance. Figure 15 and 16 illustrate examples of output histograms of slip to slip and weight to weight connection time respectively.

Rig Name	Cooper 500
Well Name	TS39
Crew Name	Cooper 500 - Total Crew
Operations Count	126
10%	1.77 min
50%	2.71 min
90%	4.53 min
Total Duration	6 hours 18 minutes
Savings Potential	2 hours 58 minutes
	47.03 %
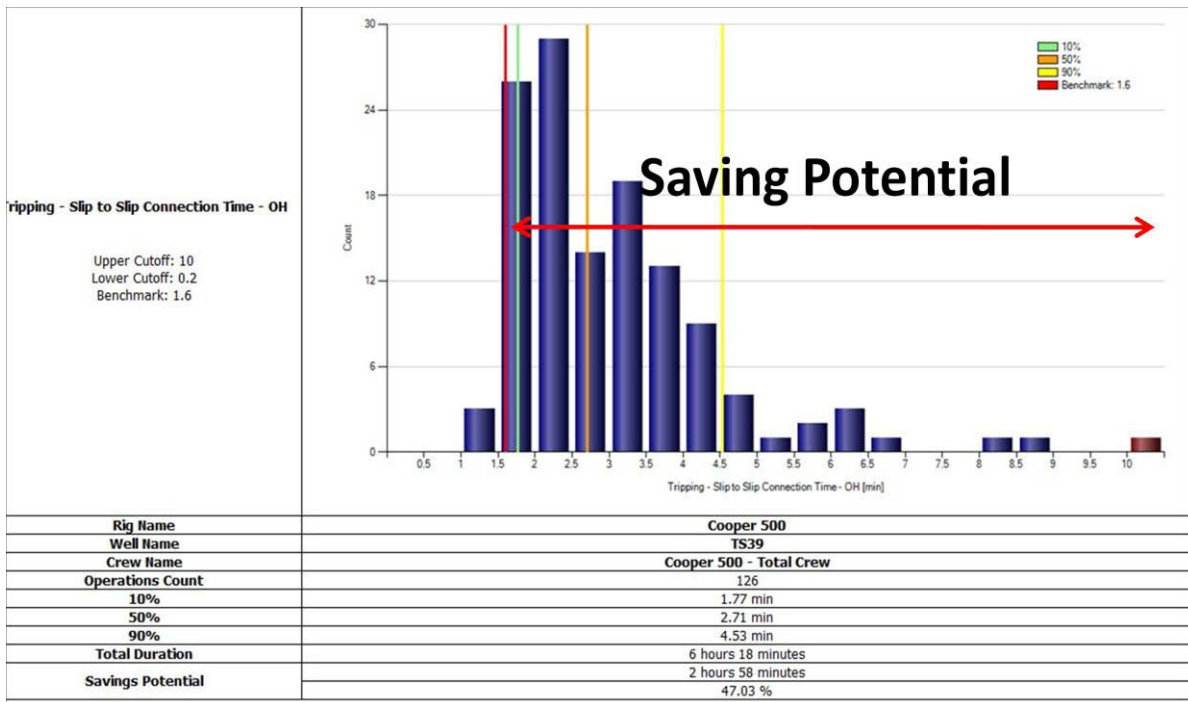
Figure 16. An Example of the Slip to Slip Connection Time Histogram Generated by ADPM
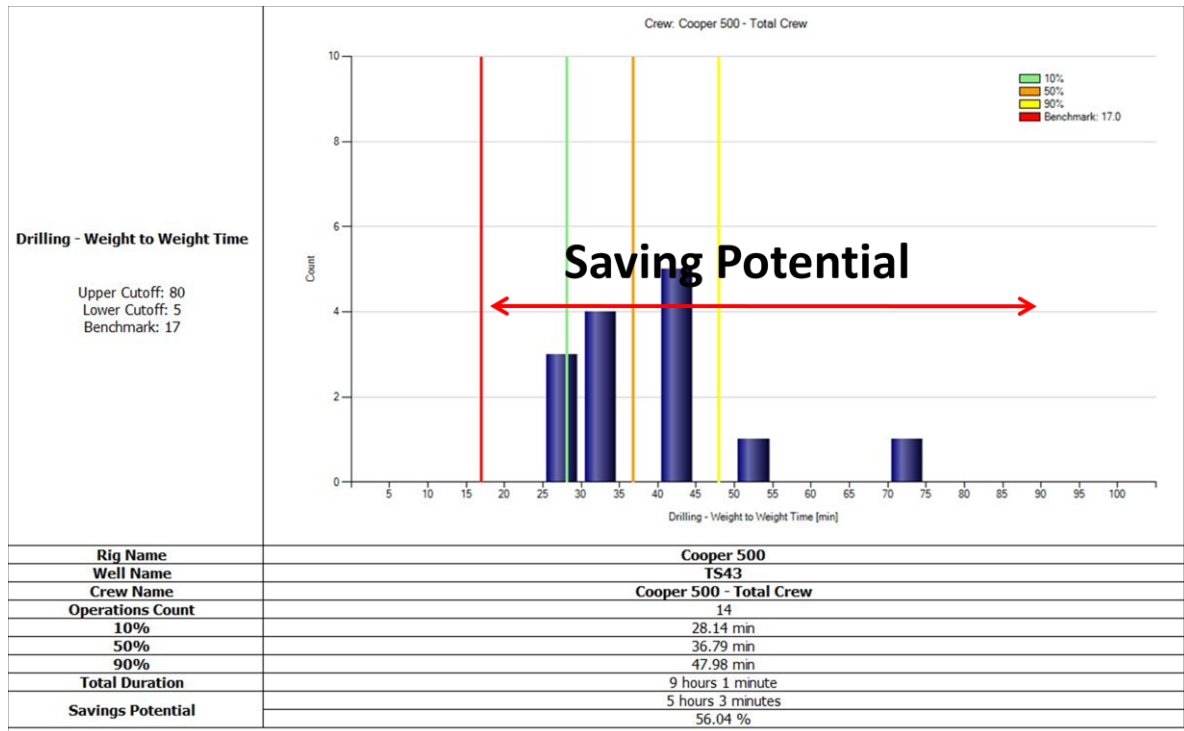
Figure 17. An Example of the Weight to Weight Connection Time Histogram Generated by ADPM

Through visual analysis of the histogram plots it becomes easy to recognize the invisible lost time. The potential of the invisible lost time is the deviation between the actual performance and the preselected target for any KPI. The selection of the target value for any KPI is a company decision; some companies set it based on the best practical time which should be a realistically achievable target, whereas the other big companies use benchmark principle. Figure 16 shows that the savings potential time is 2:58 hours and it presents 47% of the total duration. The upper and lower cut off value shown on the figures is related to the data quality control.

For a particular well once the targets values been selected for the considered KPIs based on one of the mentioned methods, consequently ADPM calculates and reports the overall savings potential. Table 3 is an example of the overall savings potential report for one well.

Slip to Slip Time

KPI	26.00"		17.50"		12.25"		8.50"	
Phase								
Operation	Tripping	Casing/Liner	Tripping	Casing/Liner	Tripping	Casing/Liner	Tripping	Casing/Liner
Operations Count	6	11	203	103	322	179	1217	11
Total Duration [h]	0.4	2.1	11.0	7.7	15.2	11.5	47.5	0.8
10% [min]	2.38	9.8	2.09	3.15	1.92	2.87	1.72	3.37
50% [min]	4.21	11.13	3.12	4.12	2.55	3.52	2.15	4.18
Benchmark [min]	2.00	2.10	2.00	2.10	2.00	2.10	2.00	2.10
Savings Potential [h]	0.2	1.7	4.3	4.1	4.6	5.2	8.4	0.4
Savings Potential [%]	46.19	81.27	38.64	53.37	29.99	45.46	17.7	48.76

Pipe Moving Time

KPI	26.00"		17.50"		12.25"		8.50"	
Phase								
Operation	Tripping	Casing/Liner	Tripping	Casing/Liner	Tripping	Casing/Liner	Tripping	Casing/Liner
Operations Count	7	13	202	103	319	179	1225	10
Total Duration [h]	0.6	1.0	8.8	4.0	10.2	8.0	31.6	0.5
10% [min]	2.92	2.77	0.95	1.6	0.85	1.85	0.75	2.48
50% [min]	5.65	4.55	2.46	1.98	1.33	2.5	1.07	2.86
Benchmark [min]	0.90	1.40	0.90	1.40	0.90	1.40	0.90	1.40
Savings Potential [h]	0.5	0.7	5.8	1.6	5.4	3.8	14.0	0.3
Savings Potential [%]	82.02	68.54	65.94	39.5	53.55	47.55	44.4	51.72

Weight to Weight Time

KPI	26.00"	17.50"	12.25"	8.50"
Phase				
Operation	Drilling	Drilling	Drilling	Drilling
Operations Count	5	42	34	10
Total Duration [h]	3.7	25.5	30.1	7.6
10% [min]	39.89	13.92	35.19	34.28
50% [min]	43.28	38.22	55.85	46.33
Benchmark [min]	29.00	29.00	29.00	29.00
Savings Potential [h]	1.3	7.7	14.1	2.8
Savings Potential [%]	34.93	30.22	46.89	37.59

Wellbore Treatment Time per Stand

KPI	26.00"	17.50"	12.25"	8.50"
Phase				
Operation	Drilling	Drilling	Drilling	Drilling
Operations Count	8	36	33	8
Total Duration [h]	1.8	7.3	5.6	2.1
10% [min]	-	-	-	-
50% [min]	-	-	-	-
Benchmark [min]	-	-	-	-
Savings Potential [h]	1.8	7.3	5.6	2.1
Savings Potential [%]	100	100	100	100

Total Savings Potential	4.3 days

Table 3. An Example of the Overall Savings Potential Report Generated by ADPM

4. Methodology Overview of the Developed Tool

4.1. Principle Workflow

The principle workflow which is introduced here shows an overview of all aspects of the developed tool.
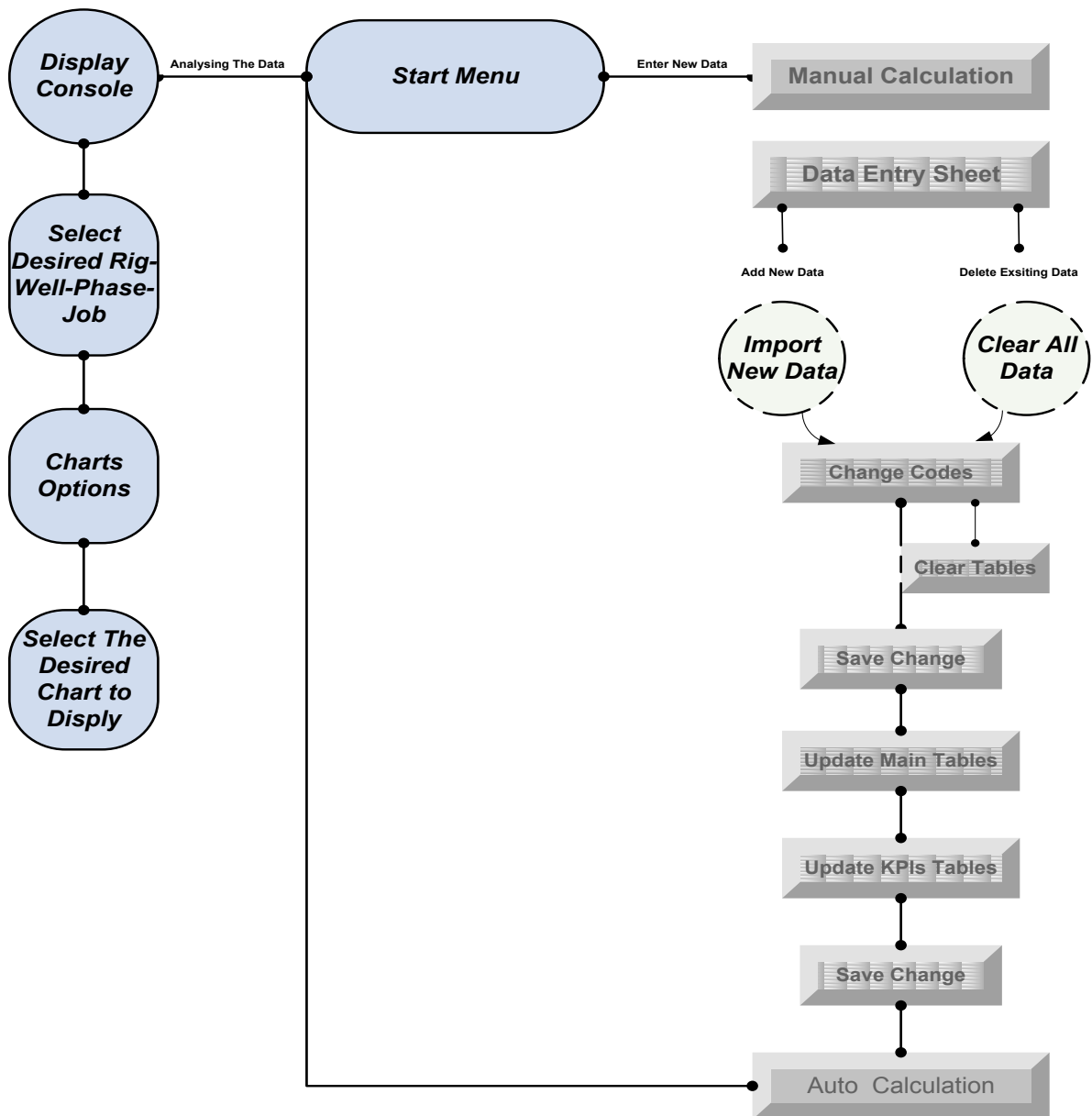
Figure 18. Developed Tool Workflow

The main objectives of the tool are to utilize meta-data and sensor data in order to calculate the overall savings potential and indicate the potential areas of improvement. Moreover, it allows the drilling engineers to analyse and track the operations of multiple rigs and services companies, the other feature that the tool offers is it's capability to recognise the invisible lost time [ILT] from non automatically detected   operations using best composite time approach [BCT].

The core data of the tool here is daily drilling report [DDR], it is used to identify the savings potential out of non automatically detected operation such as formation evaluation, run and cement casings and wait on cement, in addition it is used to determine the non productive time. The other savings potential reports from different tools are used to obtain the overall savings potential of the specific rig, well or phase.

4.2. Start Menu

The main panel of the tool contains two compartments. The first compartment is used to enter and process new data, whereas the second compartment is for displaying the results. Manual calculation must be clicked every time when it is required to go to the data entry sheet. The main function of this button is to disable all the auto calculations and increase the performance of data entry, the auto calculation must be clicked before starting viewing the results of the tools. Figure 19 shows the main panel and indicates the two compartments.

Figure 19. Developed Tool Start Menu

4.3. Processing steps

4.3.1. Data Entry Sheet

Data entry sheet is the core of the tool, as it was mentioned early in chapter 1 the daily drilling report data is the central data of the tool. There are nine fields at the data entry sheet that must be filled in right sequence in order to allow effective and successful processing and ensure the integrity of the results. These fields are the following,

- Rig name.
- Well name.
- Hrs operation Duration.
- Drilled distance.
- Phase code.
- Class code.
- Major operation code.
- Operation code
- Trouble code.

Save Change and Go to Start Menu	Go to Last Row	Clear Tables		Change The Codes		
Rig Name	Well Name	Hrs	Drilled Distance[m]	Genesis Phase Code	Genesis Class Code	Genesis Major Operation Code	Genesis Operation Code	Genesis Trouble Code

Figure 20. Developed Tool Data Entry Sheet

4.3.1.1. Changing Coding System

When new data is imported to the tool, it is necessary to press Change the Codes button. Most of the available commercial software tools are able to export the data as excel file, however, when they export the data normally they export it as codes or abbreviations, these abbreviations are not recognized by the developed software, therefore it is

necessary to click the change codes button. Appendix A shows the codes of drilling activities and their abbreviations.

4.3.1.2. Clear Tables

It is used only when data is deleted; it is not required to be used when entering new data.

4.3.2. Update Main Tables

Once the new data has been loaded into the system, update main table button has to be pressed before going to the next step of the processing.

4.3.3. Update KPIs

Update KPIs sheet is the significant advantage of the tool because here the results of other software are introduced to the system. Update KPIs sheet is divided into two fields, Field A and B.

Save and Go to Start Menu															

Field A

General Data			Optimized ROP		BOP&Well Head		WOC		Loging		Run Casing		Triping and Handle tools	
Rig Name	Well Name	Phase Size	Desired Rotating ROP m/h	Desired Sliding ROP m/h	Desired Time hr	Use The Min Time Comparison	Desired Time hr	Use The Min Time Comparison	Desired Time hr	Use The Min Time Comparison	Desired Time hr	Use The Min Time Comparison	Desired Time hr	Use The Min Time Comparison
Rig-A	Well-1	Prespud												
Rig-A	Well-1	23" Phase				DN		DN		DN		DN		DN
Rig-A	Well-1	16" Phase				DN		DN		DN		DN		DN
Rig-A	Well-1	12 1/4" Phase				DN		DN		DN		DN		DN
Rig-A	Well-1	8 1/2" Phase				DN		DN		DN		DN		DN
Rig-A	Well-1	End of Well												
Rig-A	Well-1					DN		DN		DN		DN		DN
Rig-A	Well-1					DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN
						DN		DN		DN		DN		DN

Figure 21. Developed Tool Update KPIs Sheet Field A

Field B						
Pronova Invisable Lost Time Data Entry					Extra Savings Potential Time	
Rig	Well	Phase	KPI	Savings Potential Time hr	Operation	Savings Potential Time hr
Rig-A	Well-1	23" Phase	Tripping - Slip to Slip Connection Time	15		
Rig-A	Well-1	23" Phase	BHA - Slip to Slip Connection Time	10		
Rig-A	Well-1	12 1/4" Phase	Drilling - Wellbore Treatment Time per Stand	18		
Rig-A	Well-1	12 1/4" Phase	Drilling - Weight to Weight Time	18		
Rig-A	Well-1	16" Phase	Tripping - Slip to Slip Connection Time	16		
Rig-A	Well-1	16" Phase	BHA - Pipe Moving Time	10		
Rig-A	Well-1	16" Phase	Casing and Liner - Pipe Moving Time	10		
Rig-A	Well-1	8 1/2" Phase	BHA - Pipe Moving Time	10		
Rig-A	Well-1	8 1/2" Phase	BHA - Slip to Slip Connection Time	10		

Figure 22. Developed Tool Update KPIs Sheet Field B

The general data in the Field A is updated automatically, we should note that the Pre-spud and End of the well phases are excluded. Here, optimal sliding and rotating ROP for specific cases can be entered. In addition it allows the user to deal with special KPIs which are associated with non automatically detected operations such as

- BOP and Well head work

- Waiting on Cement

- Formation evaluation

- Run casing

- Tripping in and out and handle tools

The tool offers three options for dealing with these special KPIs, the default option of the tool is DN [do nothing], the other options are Y [yes] and N [no.

If the user wants to turn the minimum time comparison feature on, then he should select Y [yes], in this case the tool will compare the target value of the specified KPI with the best practical time spent for similar operations and eventually use the minimum value of them as the official for the further processing and analysis whereas if N [no] is selected then the target value will be used.

Field B specified for entering the savings potential, which has been calculated by another tools, such as Automated Drilling Performance Measurement of Drilling Crews and Equipments [ADPM] and other tools.

Although ADPM calculates tremendous numbers of KPIs, however only the following KPIs are recognised by the tool,

- Tripping - Slip to Slip Connection Time.
- Tripping - Pipe Moving Time.
- BHA - Slip to Slip Connection Time.
- BHA - Pipe Moving Time.
- Casing and Liner - Slip to Slip Connection Time.
- Casing and Liner - Pipe Moving Time.
- Drilling - Weight to Weight Time.
- Drilling - Wellbore Treatment Time per Stand.
- Tubing - Slip to Slip Connection Time.
- Tubing - Pipe Moving Time.

The developed tool takes into account that savings potential which can be a result of optimising any drilling operation. Thus it has an extra field which allows the user to add extra savings potential.

4.4. Displaying Charts

The display console of the tool consists of two parts, selection and chart options. In the selection options the user allows to select his desired rig, well, phase and finally job. The chart options have a variety of charts associated with the selected rig, well and phase.
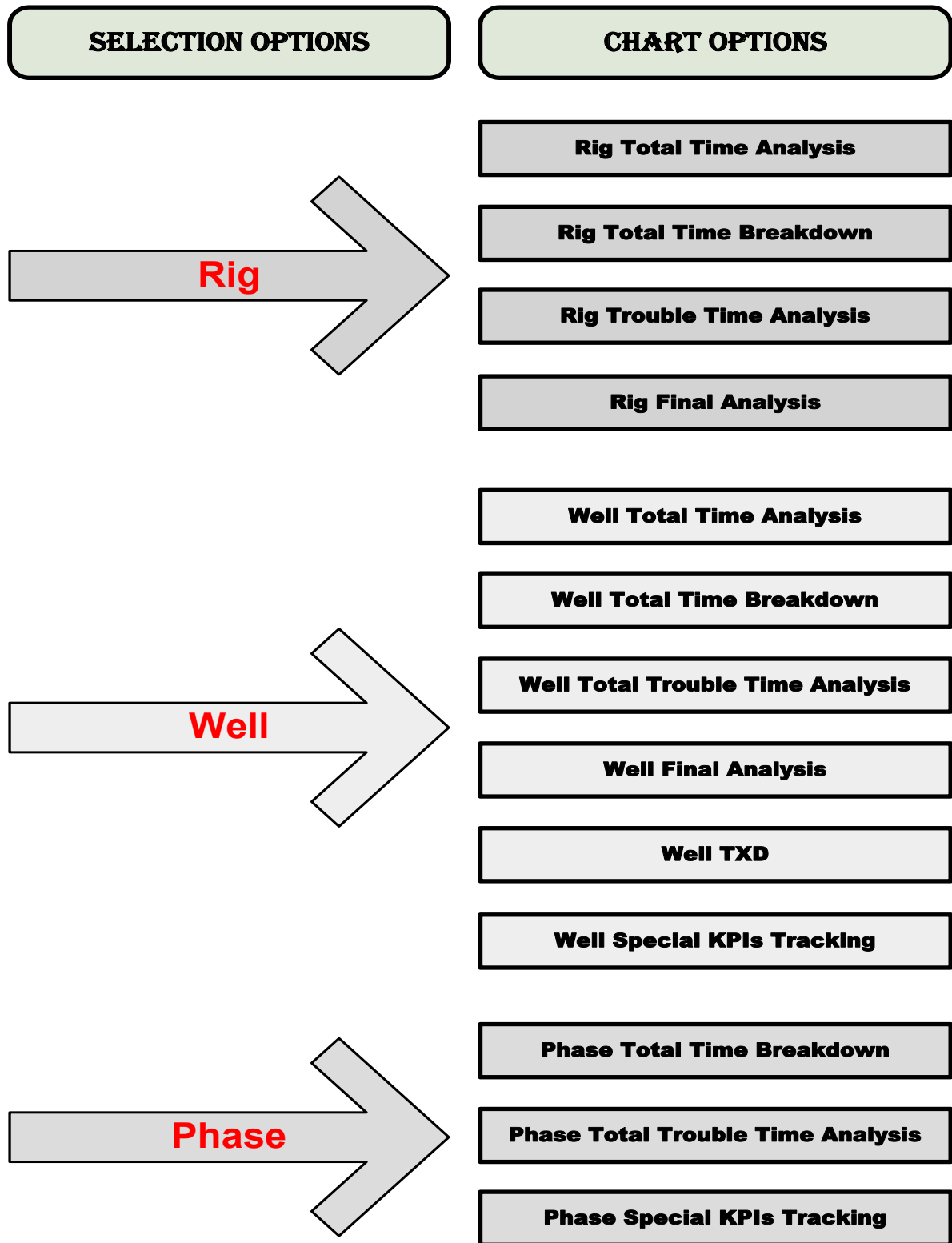
Figure 23. Display Console of the Tool with Selection and Chart Options

4.5. Tool Benefits and Report Examples

Once the daily drilling report data is loaded into the system and the desired KPIs have been identified the tool integrates the entry data and generates a variety of comprehensive charts as the output results of the tool. The tool allows the users to identify their desired rig, well, phase and job prior to commencing displaying the charts.

4.5.1. Total Time Analysis and Breakdown

- Breakdown the total time in deep details.
- Identifies how the total time has been consumed.
- Helps to identify the elements which are considered to be large time consumers.
- Shows the total non productive time.
- Identifies the percentage of the sliding drilling comparing to rotating drilling.
- Shows the total analysed time and the percentage of the savings potential.
- Breakdown the selected job in small details.
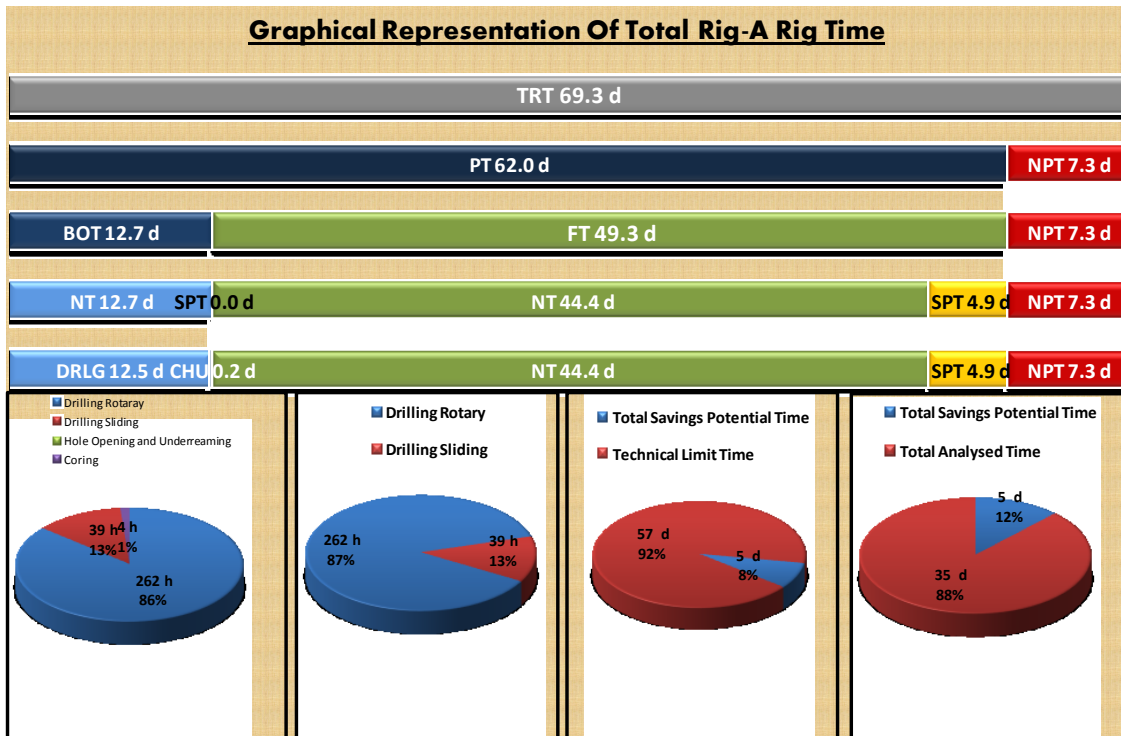
Figure 24. Rig Total Time Analysis
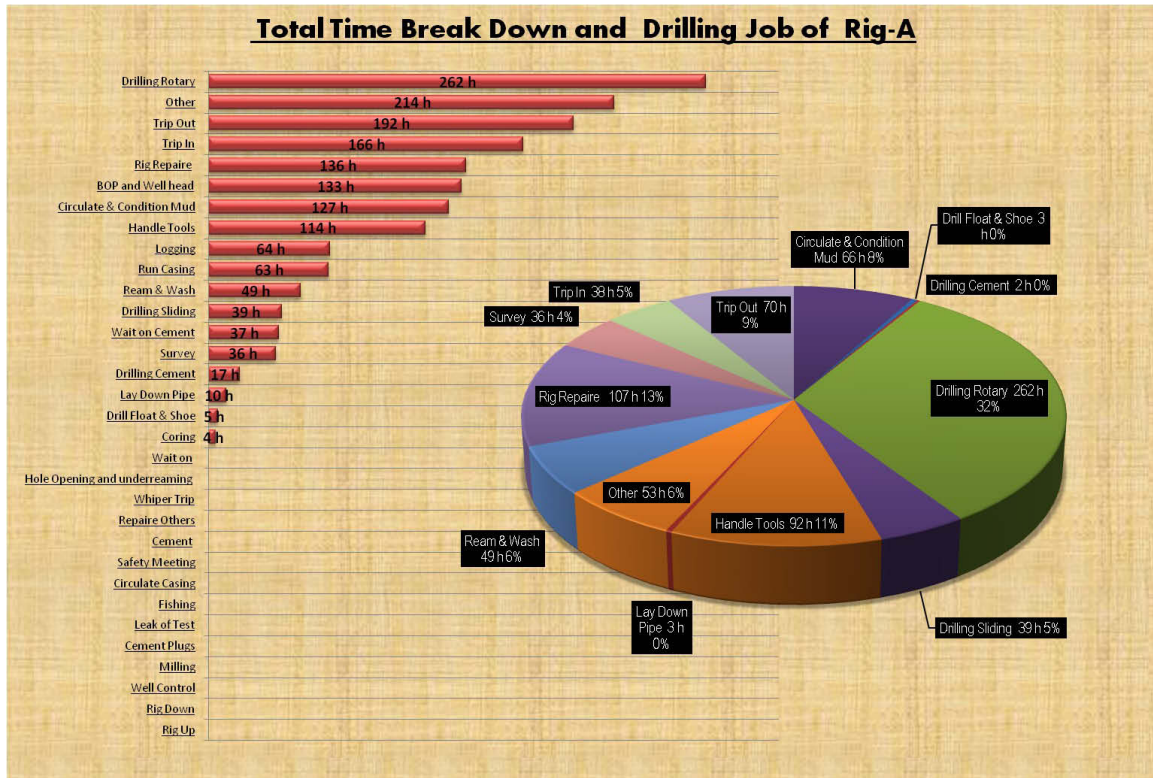
Figure 25. Rig Total Time Breakdown

4.5.2. Total Trouble Time Analysis

- It provides a simple visual way of analysing the trouble time for rigs, wells and phases.

- Indicates the potential areas.

- Indicates the causes of the trouble time.

- Helps to improve the drilling operations.

- Exposes the cause of the trouble.

- Help to improve the performance of the future wells.

- It could be used to evaluate the performance of different drilling crews and service companies.
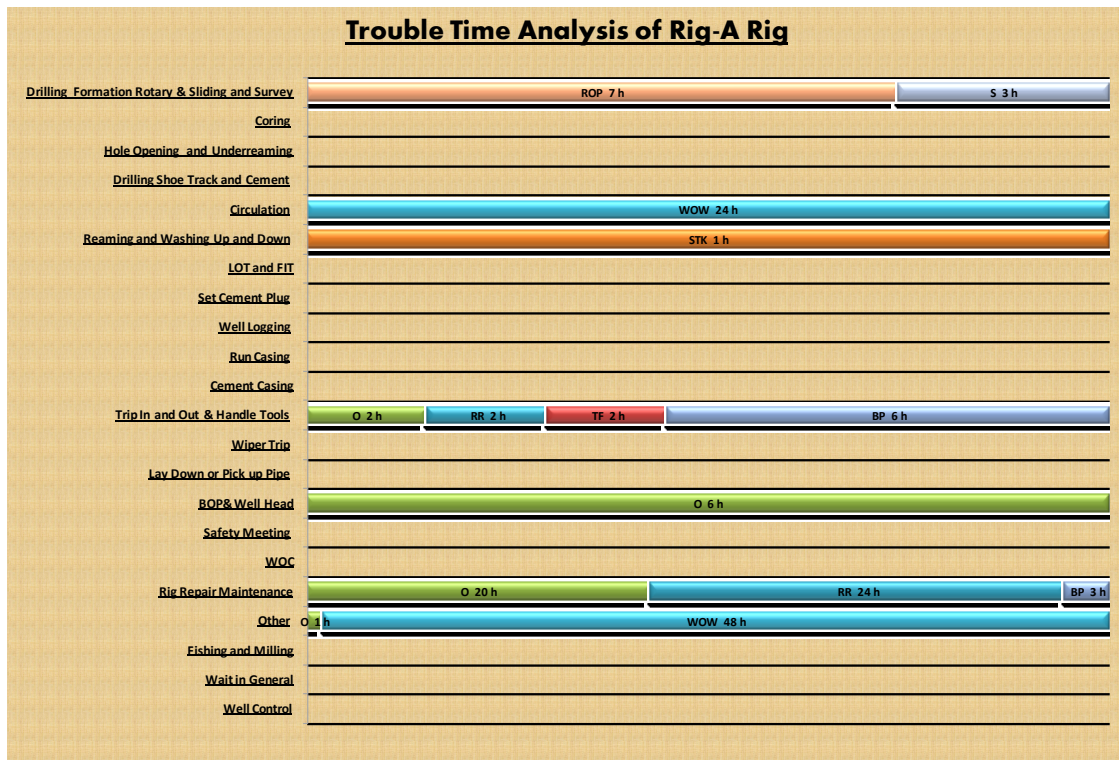
Figure 26. Rig Total Trouble Time Analysis

4.5.3. Final Analysis

- Statistically it shows the non productive time and savings potential time for different operations.

- Simply allows the users to realise drilling operation which are target for optimization.

- Helps to specify non-optimized operations.

- Identify the areas of good and bad performance.

- Help to improve the accuracy of the time forecasts for new wells.

- Identifies how the total time has been consumed [Initial Time].

- Shows the non productive time for single operations.

- Provides the method of quantifying the drilling performance by showing NPT as a percentage of the actual total time.

- Shows the ideal time duration for different operations [Final Time]
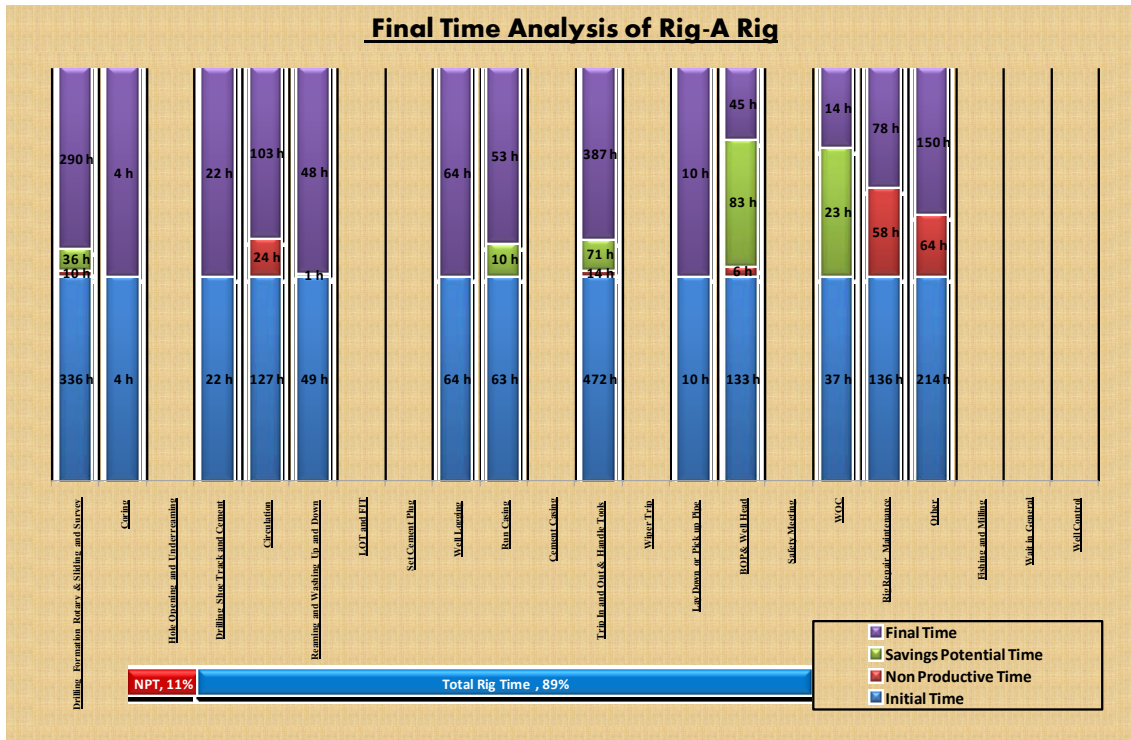
Figure 27. Rig Final Analysis

4.5.4. Time versus Depth
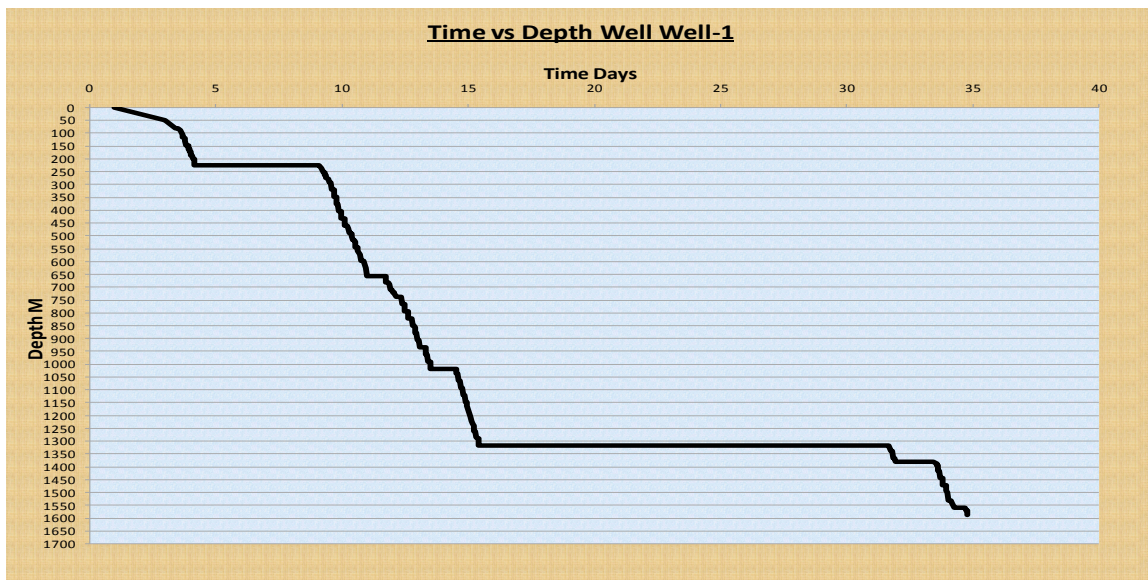
Figure 28. Well Time versus Depth [TxD]

A typical Time-versus-Depth curve is introduced here. It is the classic way of visualizing a drilling process.

The abscissa illustrates the time from the spud to the end of the well, whereas the ordinate shows the measured depth.

4.5.5. Special KPI Tracking

- Shows the three different values related to predefined special KPIs, the best practical, actual and target time.
- Allows the users to reveal if the best practical time is logical, it could be not legitimate due to human error or bad performance.
- Allows the users to recognise if the actual time which was spent is deviating from estimated time.
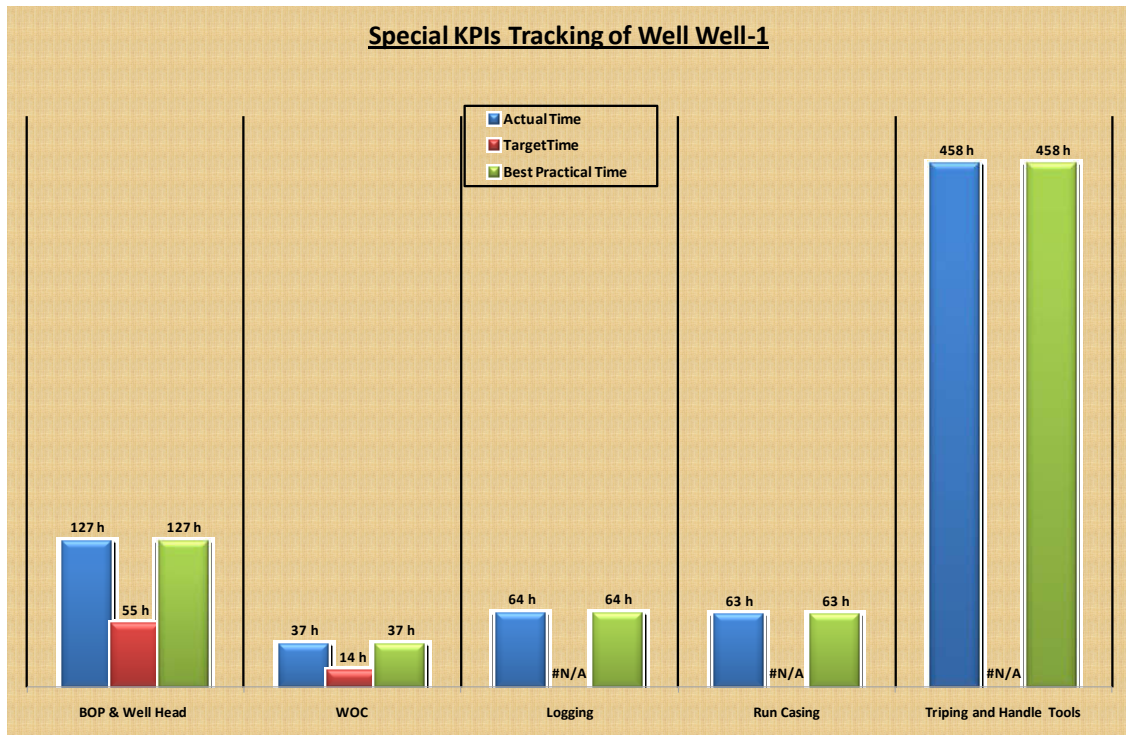
Figure 29. Well Special KPIs Tracking

The rest of the output charts of the tool can be found in Appendix C. The following table shows the description of the abbreviations which are used by the tool.

Abbreviation	Description
TRT	Total Rig Time
TPT	Total Phase Time
PT	Productive Time
NPT	Non Productive Time
BOT	Bit on Bottom Time
SPT	Savings Potential Time
NT	Necessary Time
TWT	Total Well Time
DRLG	Drilling Rotating and Sliding
CHU	Coring Hole Opening and Underreaming
d	Day
h	Hour
M	Meter
BB	Bit and Bottom Hole assembly Balling
BP	Bit Problem
BHA	Bottom Hole assembly Failure
BHS	Bore Hole Stability
BOP	Blowout Preventer
CMT	Cementing
DD	Direction Drilling
DRG	Drag
DS	Drill String
FISH	Fishing
HC	Hole Cleaning

JF	Job Failure
LOC	Loss of Circulation
MUD	Mud
NT	No Trouble
O	Other
RO	Repair Other
ROP	Rate of Penetration
RR	Rig Repair
S	Survey
STK	Stuck
TF	Tool Failure
TH	Tight Hole
TRQ	Torque
WC	Well Control
WO	Wait on
WOW	Wait on Weather

Table 4. Description of the Abbreviations which are Used by the Tool

5. Case Study

5.1. Overview

Necessary analyses for this case study performed using historical data belonging to slightly deviated wells drilled in Czech Republic Třanovice field by RWE Dea for gas storage purpose. The data of four wells drilled with two rigs was loaded to the developed tool. Table 5 shows the basic well information. Figure 29 illustrates the Stratigraphic column of Třanovice field.

Well	Well 1	Well 2	Well 3	Well 4
Total Vertical Depth TVD m	482	523	440	520
Total Measured Depth MD m	510	539	542	547
Trajectory	Deviated	Deviated	Deviated	Deviated
Max Inclination °	25	17	27	22
Drilling Rig Type	Land Rig	Land Rig	Land Rig	Land Rig
Phase sizes "	23-17 ½-12 ¼-	23-17 ½-12 ¼-	23-17 ½-12 ¼-	23-17 ½-12 ¼-
	18 5/8"-52 m	18 5/8"-52 m	18 5/8"-53 m	18 5/8"-48 m
Casing Size and Depth	13 3/8"-187 m	13 3/8"-242 m	13 3/8"-197 m	13 3/8"-303 m
	9 5/8"-335 m	9 5/8"-465 m	9 5/8"-441 m	9 5/8"-42 m
Mud Type	KCL Polymer	KCL Polymer	KCL	KCL

Table 5. Basic Well Information
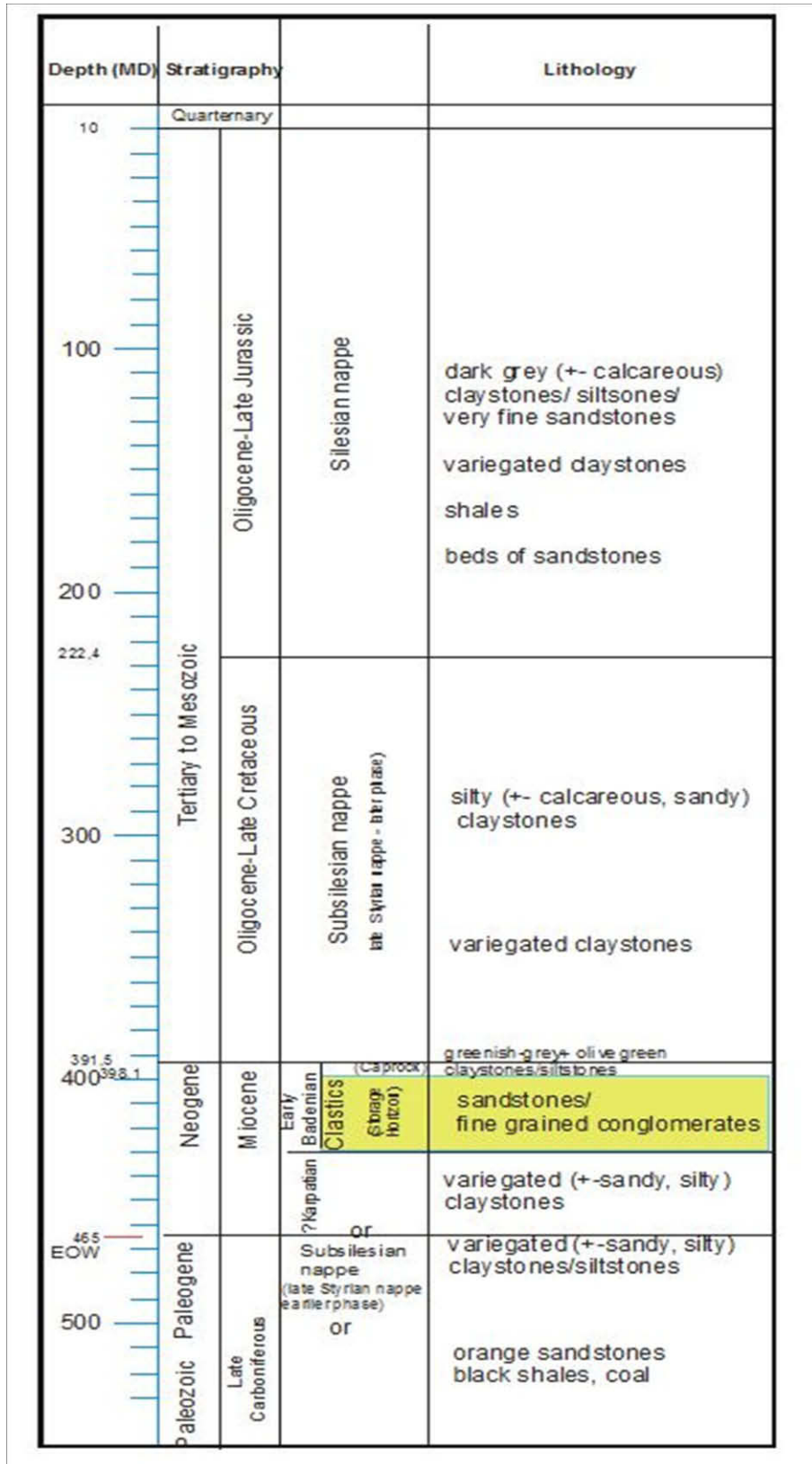
Figure 30. Stratigraphy Column of Třanovice Field

Five formations have been encountered while drilling the four wells the following table shows the four wells and the base of the formations as it recorded by the geologist.

Formation Base [Measured Depth m]					
Well Name	Quaternary	Silesian	Subsilesian	Pelitic facies	Basal clastics
Well 1	10	275	385	408	485
Well 2	10	288	399	436	488
Well 3	10	324	448	458	550
Well 4	10	342	407	450	527

Table 6. Wells and Formation Base

5.2. Pre-Analysis Performance

Based on the total time breakdown of the both rigs we highlight the following comments regarding to the time consumers

- The combination of trip in and trip out operations is one of the largest time consumers. It consumed 16.2% and 20% of the total rig time for Rig A and B respectively.
- The second obvious consumer is the BOP and well head work. The total time in hours spent for the BOP and well head was 322 hrs for Rig A and 260 hrs for Rig B.
- The drilling time [Rotating and Sliding] comprises another large element of total well construction time.
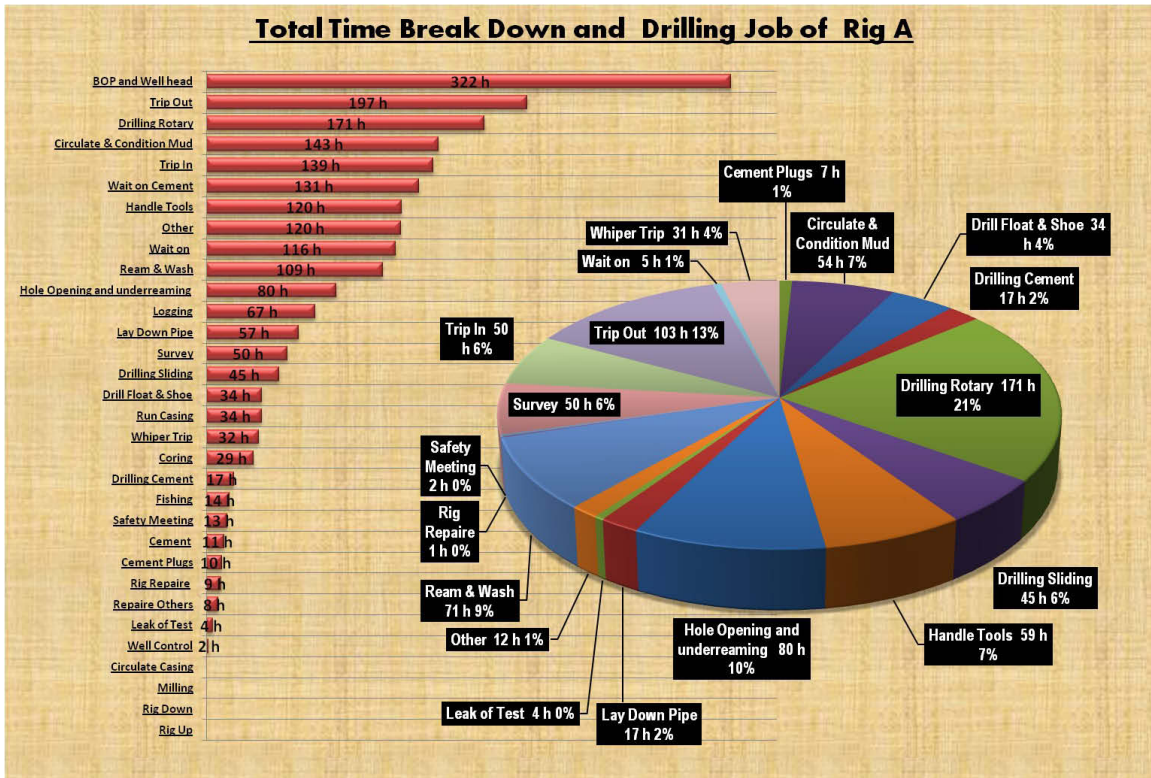
Figure 31. Pro-Analysis Total Time Breakdown Rig A
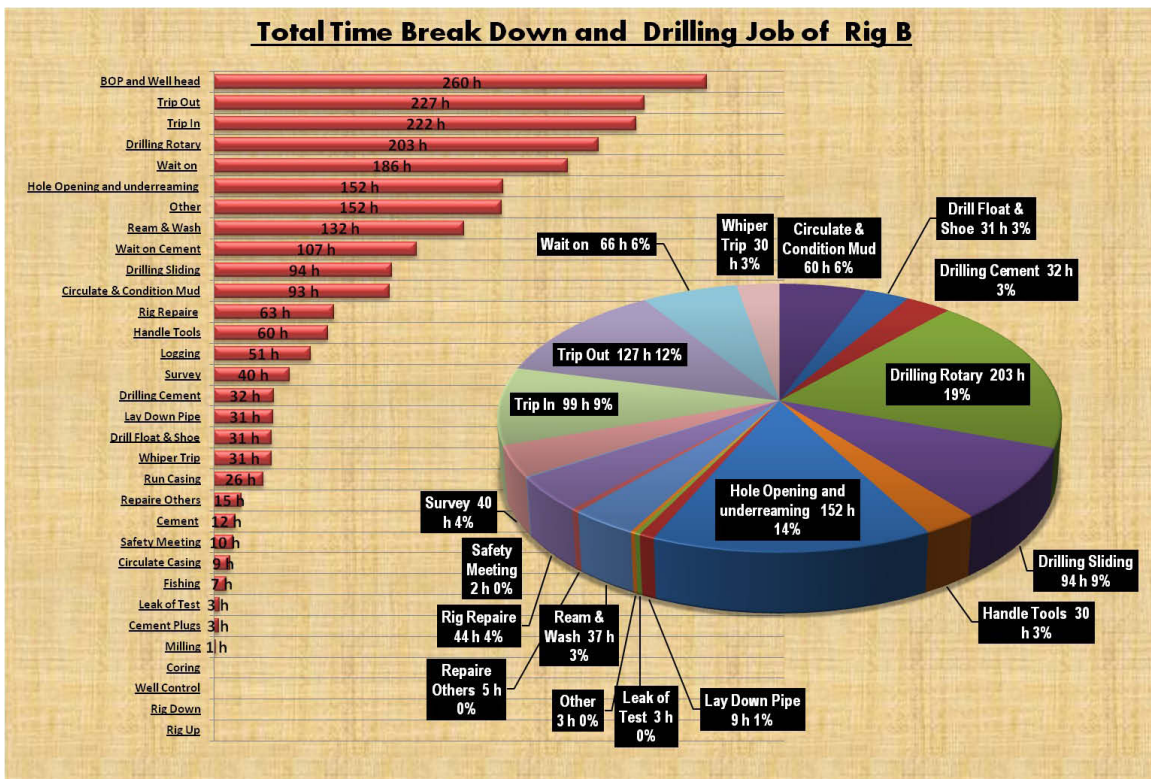
Figure 32. Pre-Analysis Total Time Breakdown Rig B

Concerning the large element time consumers, calculation of the savings potential and develop a focus for further analysis, the following study were performed.

- ❖ Analysis of saving potential from routine drilling operations and invisible lost time [ILT]. Dealing with Tripping elements and other surface routine operations.
- ❖ Analysis of saving potential from optimizing rate of penetration [ROP].

5.3. Analysis of Saving Potential from Routine Drilling Operations and Invisible Lost Time [ILT]

Automated Drilling Performance Measurement ADPM tool was used to efficiently identify the hidden lost time of the routine drilling operations in this study. The principle of the tool was described in Chapter 3, in this part only the setting of the benchmark will be explained plus the final results.

5.3.1. Benchmark

The criteria used to set the benchmarks for this study was based on the best practical time derived from measurements which can be possibly achieved.

The summary of the interested KPIs and their benchmarks which used for this study is shown in Table 7, whereas Figure 33 and 34 show the histograms of drilling weight to weight time for Rig A and B respectively.

The remaining histograms of the KIPs of interest and selected benchmarks for both rigs are included in Appendix D.

KPI Description	Benchmark Minute
Drilling Wellbore Treatment Time per Stand	0
BHA - Slip to Slip Connection Time	4
BHA - Pipe Moving Time	1
Drilling - Weight to Weight Time Top Hole	14
Drilling - Weight to Weight Time	17
Tripping Slip to Slip Connection Time	1.75
Tripping Pipe Moving Time CH	0.33
Tripping Pipe Moving Time OH	0.66
Surface Casing Slip to Slip Connection Time	8
Surface Casing Pipe Moving Time	1
Casing Slip to Slip Connection Time	3
Casing Pipe Moving Time	1
Tubing Slip to Slip Connection Time	3
Tubing Pipe Moving Time	1

Table 7. Summary of the Benchmarks and the KIPs of Interest Used for Case Study
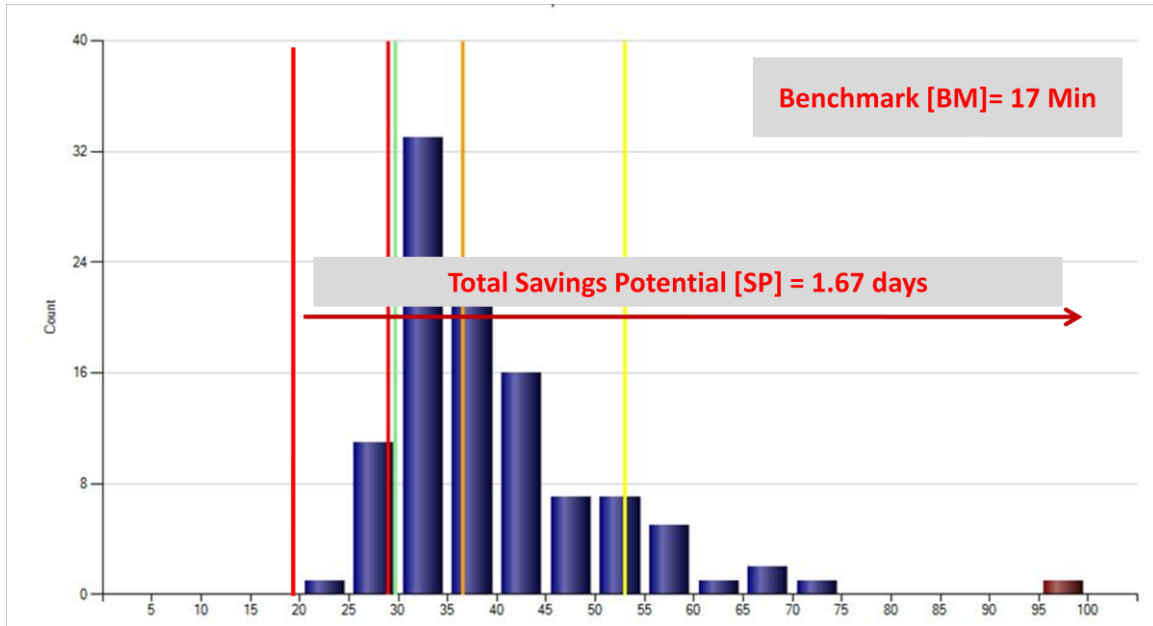
Figure 33. Drilling Weight to weight time Histogram Rig A
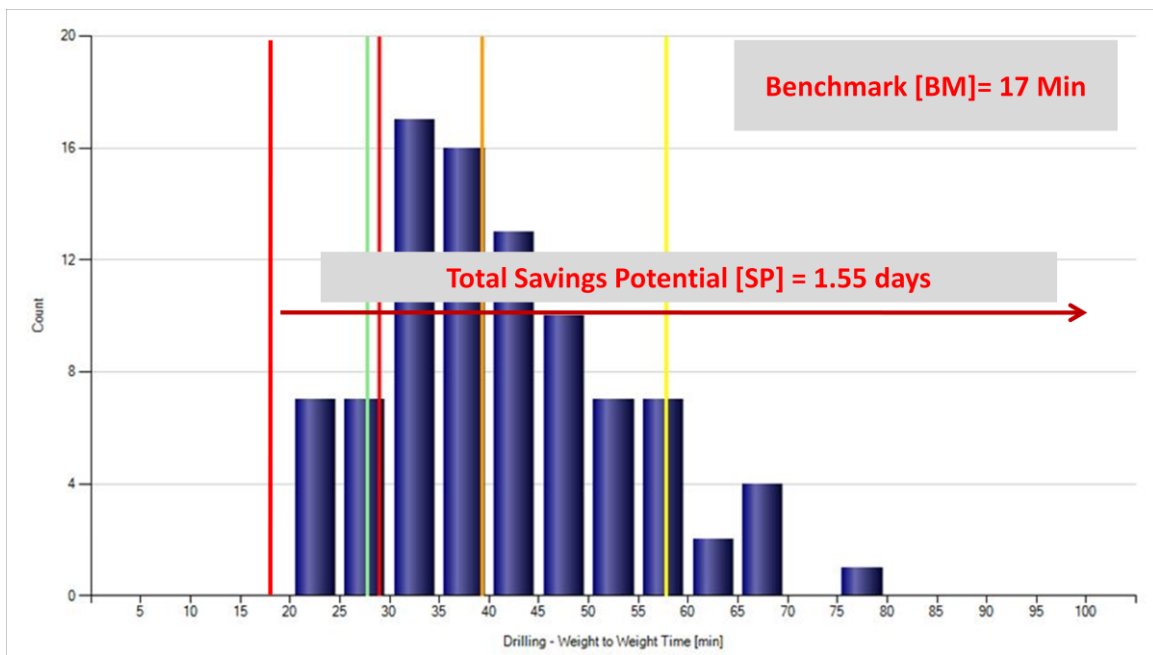
Figure 34. Drilling Weight to weight time Histogram Rig B

5.3.2. Savings Potential Report

As it was mentioned in chapter 3 one of the most powerful feature of ADPM is the generation of the total savings potential report, it generates such a report for every single well. The savings potential reports of the four wells are summarized in Table 8.

KPI	Savings Potential in Hours			
	Well 1	Well 2	Well 3	Well 4
BHA Slip to Slip Time	8.5	13	5	12
BHA Pipe Moving Time	7.5	4	5	8.5
Tripping Slip to Slip Time	8	7	5.5	11
Tripping Pipe Moving Time	13	14	7.5	15
Casing Slip to Slip Time	2.7	4	1	2
Casing Pipe Moving Time	1	1	1	1
Tubing Slip to Slip Time	NA	1	NA	NA
Tubing Pipe Moving Time	NA	1	NA	NA
Weight to Weight Time	15	22	18	22
Well Bore Treatment Time	5.5	5	7	8.5
Total in Days	**2.5**	**3**	**2**	**3.3**

Table 8. Summary of the Savings Potential Reports of the Four Wells
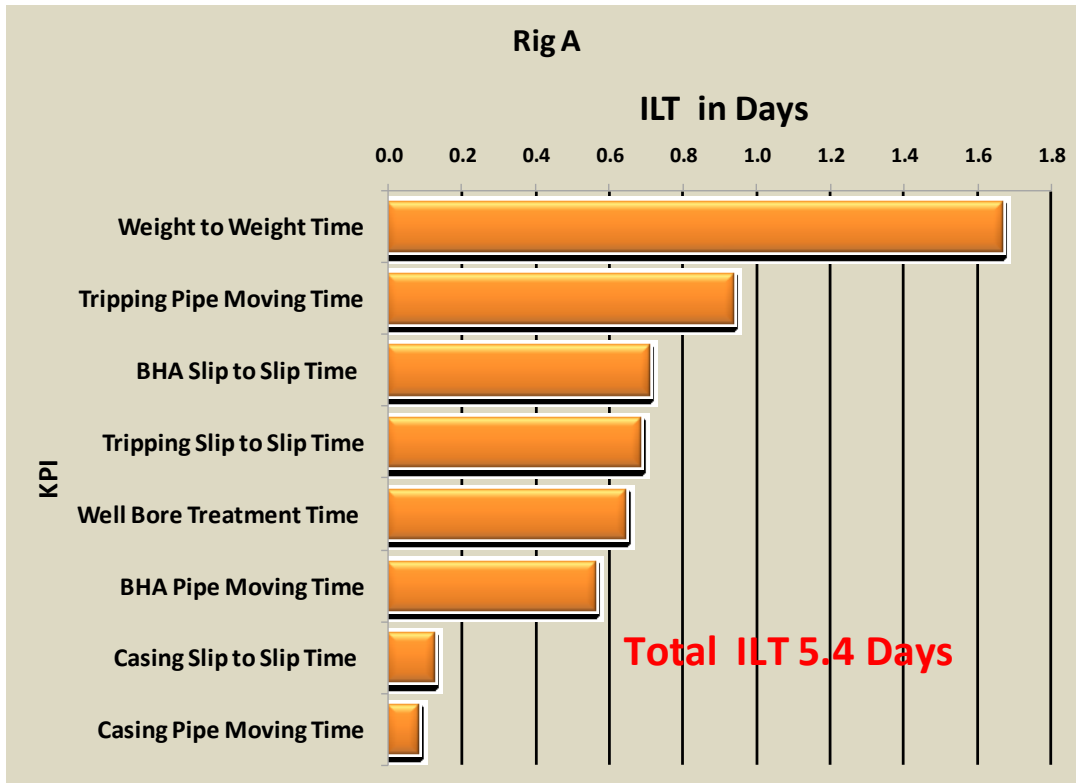
Figure 35. KPIs Ranking and ILT of Rig A
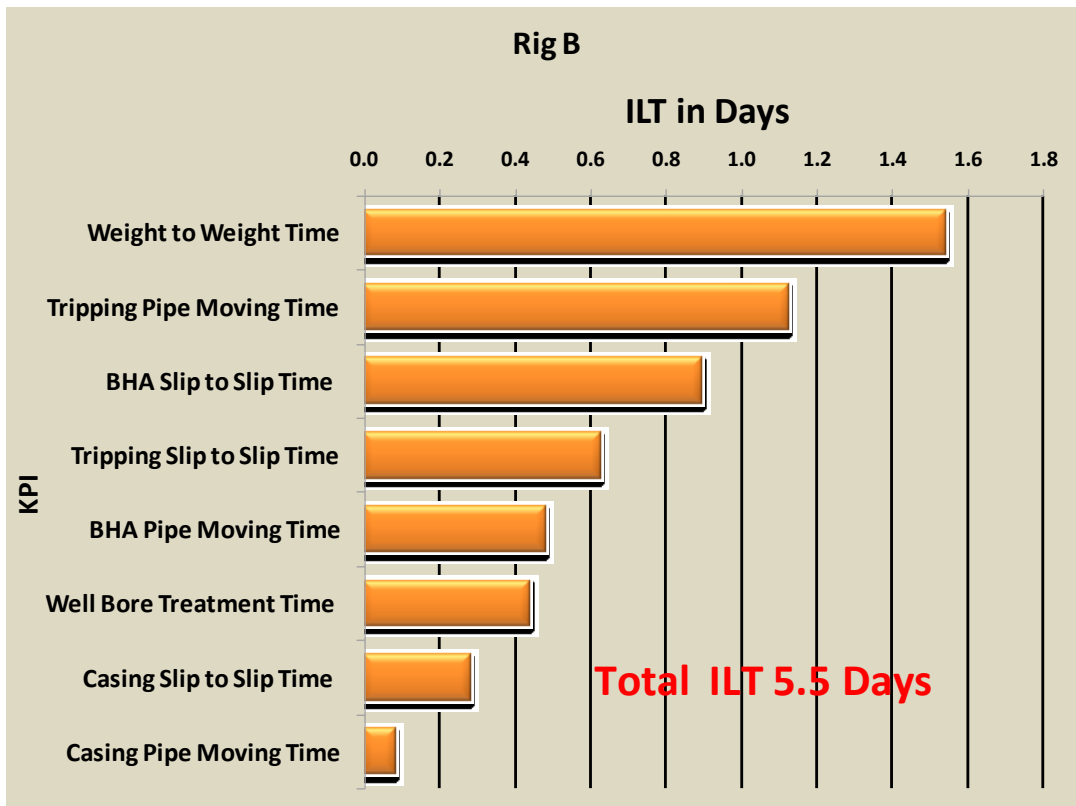
Figure 36. KPIs Ranking and ILT of Rig B

5.4. Analysis of Savings Potential from Optimizing Rate of Penetration [ROP]

Optimizing ROP of the historical data can help to

- Measure the performance of BHAs and bits.
- Select the optimal drilling parameters for future drilling operations.
- Identify the savings potential time.

As it mentioned earlier in Chapter 3 the instant ROP and DSE are connected; hence by optimizing and controlling DSE we can optimize ROP.

In order to perform better analysis it was necessary to split the study into two sections. The first section explains the method used to the define the optimal mathematically ROP, the resultant rotating and sliding ROPs of this study for different phases were integrated later to the developed tool to calculate the overall savings potential.

The second section has been specified to identify inefficient drilling conditions that caused low ROP for different formations.

5.4.1. Data Description

The data used here is the drilling parameters data generated by the surface sensors and gathered at the mud logging unit. This data has the resolution of five second (data recorded every five second), and was captured in Excel format.

The first step was to extract the drilling intervals form the entire data since drilling intervals are the interesting part here.

In order to calculate the drilling specific energy by using equation 6 other factors were calculated for every single set of data. Table 9 shows the main data whereas Table 10 depicts the calculated data.

Duration	In [hour]
TMD	Total Measured Depth [meter]
WOB	Weight on Bit [Ibf]
SPP	Stand Pipe Pressure [psi]
RPM	Surface [RPM]
FR	Flow Rate Gallon per minute [gpm]
Tq	Surface Torque [Ibf ft]
Bit Size	In [inch]
TFA	Total Nozzle Area of the Bit in [inch square]
ρ	Mud Weight [Pound per gallon ppg]
Phase Size	In [inch]

Table 9. Main Data Generated by Surface Sensors Used for Optimising ROP

TOB	Torque on Bit calculated by Eq 3
Down RPM	Obtained from Figure37, It Based on Down Hole Motor Specification and Flow Rate
ΔP bit	Pressure Drop Cross the Bit calculated by Eq 7
Bit hp	Bit Horsepower calculated by Eq 8
Bit Area	Total Bit Area In [inch]
Λ	Bit hydraulic factor obtained from Figure 6

Table 10. Calculated Data Used for Optimising ROP

$$\Delta p \; bit = \frac{8.311 * 10^{-5} * \rho * FR^2}{0.95^2 * TFA^2}$$
Eq 7

$$Bit\ Hp = \frac{\Delta pbit * FR}{1714}$$

Eq 8
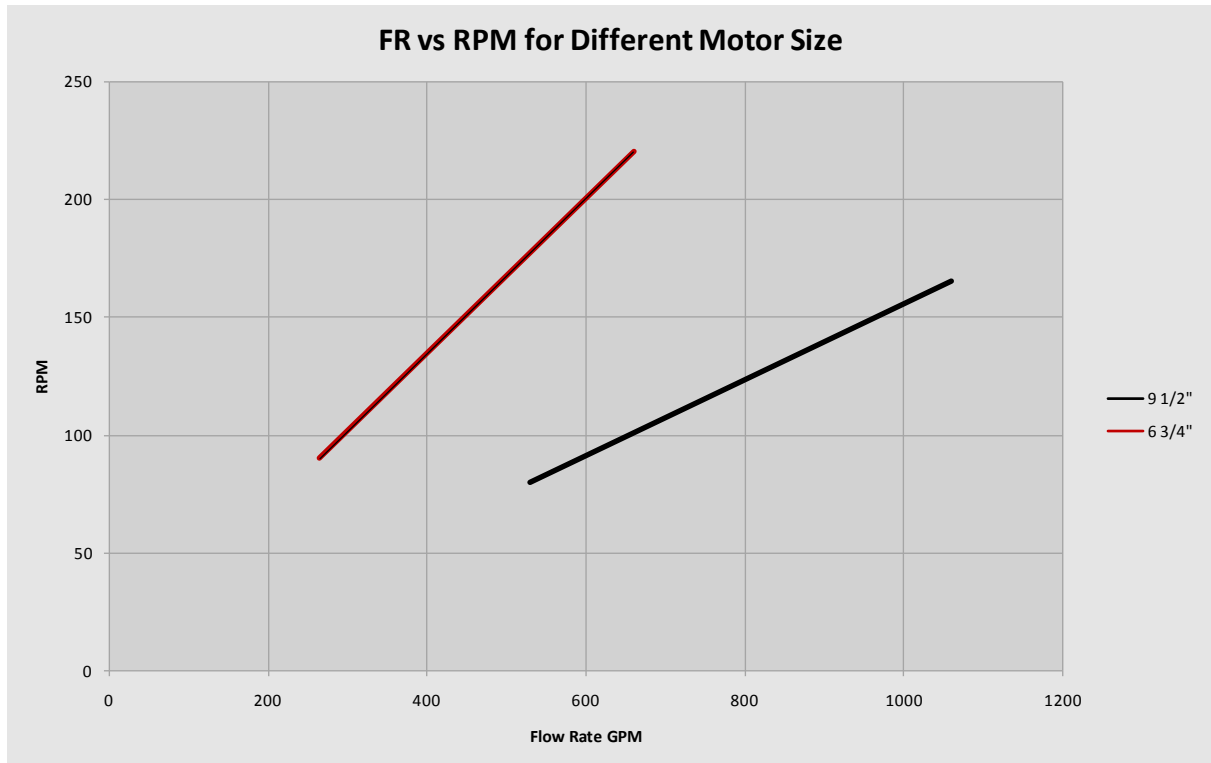
Figure 37. Down Hole RPM, RPM vs Flow Rate of Different Motor Sizes Baker Book

5.4.2. Data Filtering

One most important observation considered having an impact to the quality and the accuracy of the results of an optimization study is the data quality. The data should be as consistent as possible. Noisy data distracts the processability of the data. Data filtering is always considered as necessary for the data to be processed. Therefore the data of both studies had passed multiple filters at different stages during the processing.

5.4.3. Process to Obtain the Optimal Theoretical ROP

The process commenced by applying three different filters setting sequentially.

5.4.3.1. First Filter

A first filter was for eliminating the data errors caused by malfunction of the sensors and to differentiate between the sliding and rotating drilling, the dominant factors here are weight on bit, surface RPM and surface torque.

12 1/4" Phase Rotating Data										
Depth	Duration hr	TOB lbf ft	Total RPM	WOB lbf	Bit Area in2	DSE Psi	Bit Size in	Bit HP	ʎ Hyd Fac	ROP ft/hr
616.8592-617.8592	0.1056	428	128	5027	118	17716	12.25	50	0.008383709	9
617.8592-618.8592	0.1056	482	127	5670	118	20036	12.25	50	0.008383709	9
618.8592-619.8592	0.1861	618	127	7270	118	45492	12.25	51	0.008383709	5
619.8592-620.8592	0.1361	667	127	7838	118	36038	12.25	51	0.008383709	7
620.8592-621.8592	0.1222	737	127	8669	118	35716	12.25	51	0.008383709	8
621.8592-622.8592	0.1556	393	126	4625	118	23668	12.25	51	0.008383709	6
622.8592-623.8592	0.0819	266	127	3123	118	8294	12.25	51	0.008383709	12
623.8592-624.8592	0.1153	328	127	3857	118	14541	12.25	51	0.008383709	9
624.8592-625.8592	0.1514	348	127	4087	118	20341	12.25	51	0.008383709	7
625.8592-626.8592	0.2153	134	128	1576	118	10308	12.25	51	0.008383709	5
626.8592-627.8592	0.1597	456	115	5366	118	25713	12.25	54	0.008383709	6
627.8592-628.8592	0.0736	872	109	10254	118	21946	12.25	53	0.008383709	14
628.8592-629.8592	0.0806	835	110	9811	118	23027	12.25	54	0.008383709	12
629.8592-630.8592	0.0583	872	109	10247	118	17332	12.25	54	0.008383709	17
630.8592-631.8592	0.0319	898	107	10560	118	9692	12.25	53	0.008383709	31
642.8592-643.8592	0.008333333	115.3408033	111.692713	1355.842912	117.8588119	285.5583864	12.25	59.07960432	0.008383709	120
643.8592-644.8592	0.027777778	582.236624	112.4866708	6844.250927	117.8588119	5646.067992	12.25	59.10917995	0.008383709	36
644.8592-645.8592	0.036111111	775.5027992	111.4777885	9116.114538	117.8588119	9764.163025	12.25	58.77971985	0.008383709	27.69230769
645.8592-646.8592	0.044444444	928.1769824	112.181437	10910.81514	117.8588119	14526.30658	12.25	58.92890191	0.008383709	22.5
646.8592-647.8592	0.054166667	821.5958407	111.481811	9657.942944	117.8588119	15499.15366	12.25	59.28611377	0.008383709	18.46153846
647.8592-648.8592	0.041666667	839.3934772	109.4502606	9867.155977	117.8588119	11983.47757	12.25	58.74038092	0.008383709	24
648.8592-649.8592	0.041666667	822.3267893	110.4372242	9666.535319	117.8588119	11838.82793	12.25	59.10841956	0.008383709	24
649.8592-650.8592	0.034722222	889.5682895	109.1216307	10456.96602	117.8588119	10581.03492	12.25	59.07048458	0.008383709	28.8
650.8592-651.8592	0.056944444	935.625933	112.903529	10998.37831	117.8588119	18857.99811	12.25	59.40338648	0.008383709	17.56097561
651.8592-652.8592	0.038888889	884.4804339	112.2826391	10397.15775	117.8588119	12117.70766	12.25	59.18331252	0.008383709	25.71428571
652.8592-653.8592	0.038888889	917.3679684	112.367147	10783.75408	117.8588119	12590.27892	12.25	59.12797821	0.008383709	25.71428571
653.8592-654.8592	0.045833333	897.2656329	111.8480926	10547.44907	117.8588119	14420.29954	12.25	59.19958899	0.008383709	21.81818182
654.8592-655.8592	0.038888889	906.1152071	110.3654901	10651.47672	117.8588119	12206.27153	12.25	59.12490007	0.008383709	25.71428571
655.8592-656.8592	0.068055556	920.8509659	111.9553026	10824.69707	117.8588119	21972.95095	12.25	58.54391016	0.008383709	14.69387755
656.8592-657.8592	0.038888889	925.8075394	110.3180815	10882.9621	117.8588119	12479.84193	12.25	57.89858132	0.008383709	25.71428571
657.8592-658.8592	0.056944444	923.0466267	112.1970691	10850.50729	117.8588119	18489.12734	12.25	58.1747994	0.008383709	17.56097561
658.8592-659.8592	0.068055556	918.8224069	112.9858301	10800.85115	117.8588119	22131.07862	12.25	58.37211233	0.008383709	14.69387755

Figure 38. Output Data after Applying the First Filter

5.4.3.2. Second Filter

The second filter was applied to remove outliers (Data points were considered being out of specified range)

Figure 39 illustrates an example of the output data after applying the second filter.

Rotating							
DSE Psi	ROP ft/hr	TOB ibf ft	Total RPM	WOB lbf	Bit Area in2	Bit Size in	Bit HP
274.44	72	69.4	119.7	815.7	117.9	12.25	51.9
277.44	90	86.7	114.4	1019.6	117.9	12.25	53.6
304.88	72	73.2	123.5	860.4	117.9	12.25	53.2
321.54	80	83.4	122.0	980.5	117.9	12.25	53.3
324.36	90	91.5	122.4	1075.5	117.9	12.25	52.8
371.64	90	100.9	123.4	1185.8	117.9	12.25	51.7
386.14	60	78.2	120.0	919.3	117.9	12.25	51.9
401.20	65	92.1	112.8	1082.3	117.9	12.25	53.8
404.63	90	105.5	129.6	1240.1	117.9	12.25	58.7
420.34	55	78.0	121.2	916.4	117.9	12.25	52.3
444.50	51	75.1	124.6	882.5	117.9	12.25	52.8
462.67	72	99.4	128.1	1168.4	117.9	12.25	57.7
488.06	60	107.7	119.5	1265.8	117.9	12.25	88.8
527.68	80	129.3	116.9	1519.8	117.9	12.25	50.9
547.49	90	145.3	121.4	1708.6	117.9	12.25	60.1
561.29	65	112.6	120.6	1323.7	117.9	12.25	52.7
563.94	65	109.2	125.8	1283.6	117.9	12.25	55.0
567.84	65	112.6	121.8	1323.7	117.9	12.25	52.8
575.55	72	123.9	121.1	1456.1	117.9	12.25	52.7
577.11	65	114.3	121.6	1343.8	117.9	12.25	52.7
580.44	72	125.7	122.1	1477.1	117.9	12.25	58.2
593.17	72	121.9	128.9	1433.0	117.9	12.25	59.8
595.63	60	124.6	119.1	1464.2	117.9	12.25	88.4
601.35	65	133.7	119.3	1571.3	117.9	12.25	88.8
607.46	65	121.1	122.0	1423.0	117.9	12.25	58.7
610.46	72	129.5	121.8	1522.3	117.9	12.25	52.8
613.90	72	132.4	131.6	1556.5	117.9	12.25	88.6
632.79	72	123.9	134.3	1456.1	117.9	12.25	60.8

Figure 39. Output Data after Applying the Second Filter

5.4.3.3. Third Filter

The last filtering process presented here is deemed as real-time optimizer, where parameters are searched which minimize DSE and maximize ROP. However, the ideal method to identify the most efficient drilling parameters is by calculating the mechanical efficiency using Eq 5. The problem here is the lack of the UCS data. Therefore the following steps were followed in order to use the DES for identifying the optimal ROP according to Figure 8.

➢ The first step was to group the data based on WOB.
➢ The second step was to define the boundaries of the transition zone, special the upper boundary.
➢ The last step was to filter the date and identify the data which has the DSE below the upper boundary of the transition zone see Figure 40.
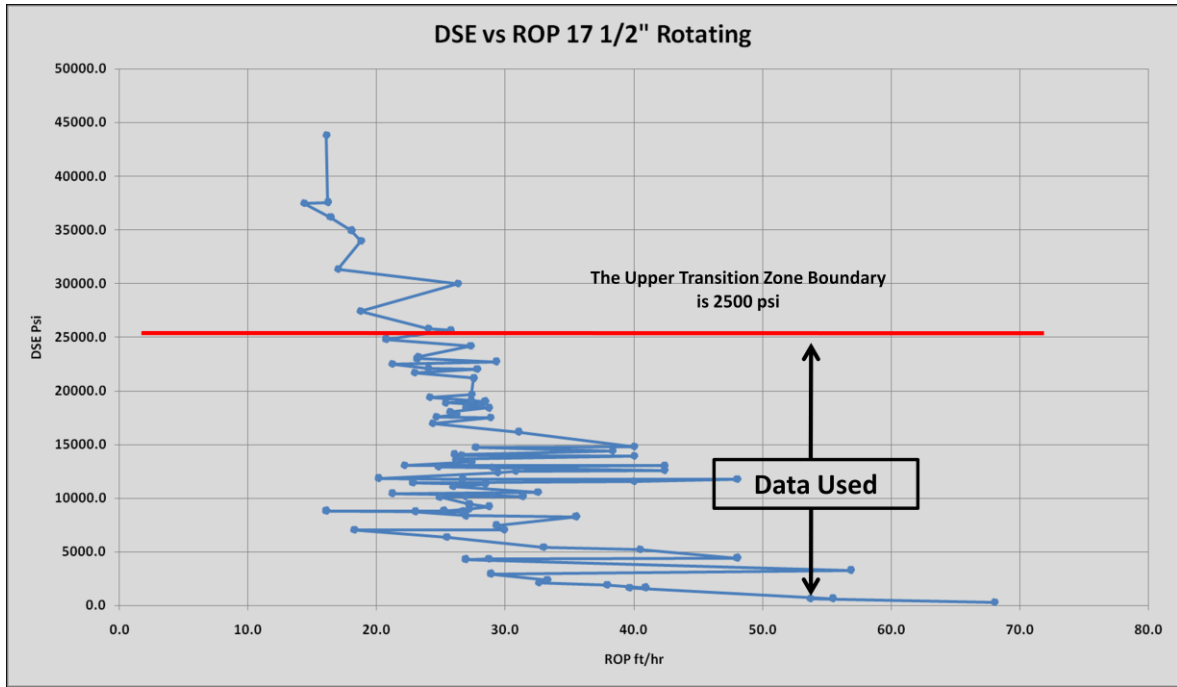
Figure 40. An Example of How to Identify the Upper Boundary of the Transition Zone

The Upper Boundary of the Transition Zone for Different Phases			
Phase	17 ½"	12 ¼"	8 ½"
Rotating	2500	4000	4000
Sliding	1500	3000	3500

Table 11. Summary of the Upper Boundary of the Transition Zone for Different Phases

Filter. No	Setting
1	WOB>500Ibf, Surface Tq and RPM=0 for Sliding
2	0<ROP ft/hr<100
3	DSE<XXX Psi See Table 11

Table 12. Generic Settings of Filtering Process

5.4.3.4. Probability Distribution and Optimal Theoretical ROP

In order to determine the optimal theoretical ROP from the processed data one of the commercial probability distribution software tools "Easyfit" was used[10].

The resulting rotating and sliding ROPs for different phases were loaded into "Easyfit" to select the best predefined model that fit the data. The optimal theoretical ROPs were selected to be the values which represent P50 for the entire cases.
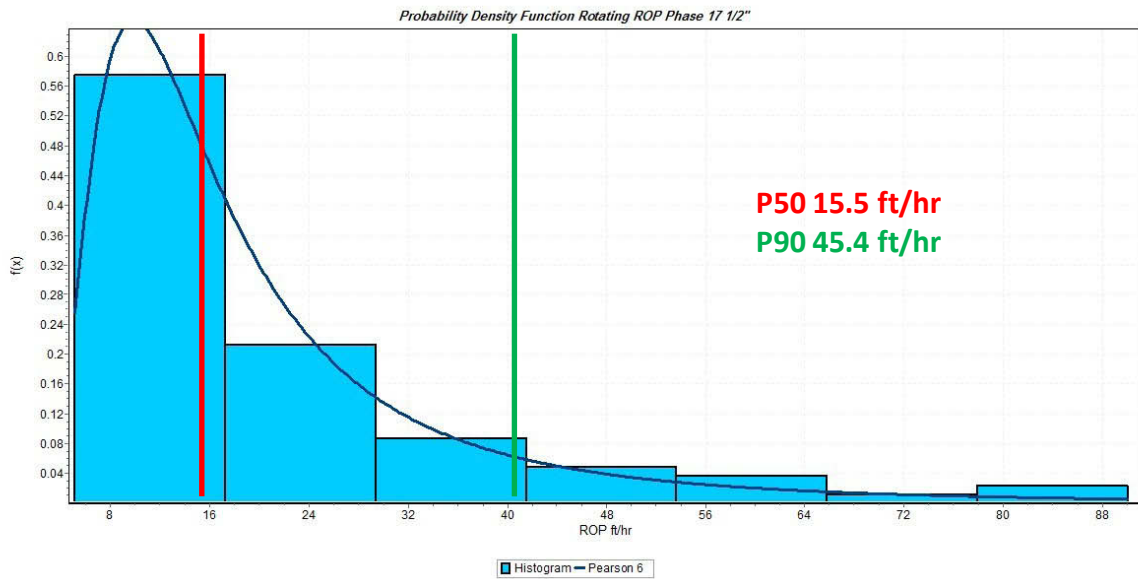
Figure 41. Probability Density Function 17 ½" Phase Rotating ROP Plus P50 and P90
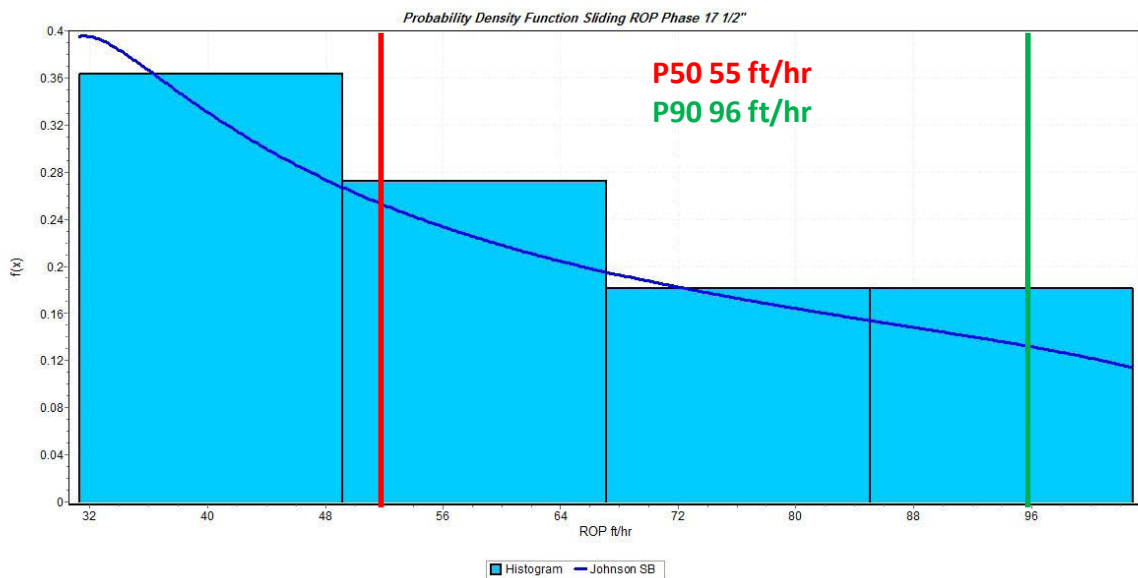
Figure 42. Probability Density Function 17 ½" Phase Sliding ROP Plus P50 and P90

Appendix E shows the remaining probability distributions of sliding and rotating ROPs for different phases. The following table shows the final results, the ROP data shown here is the data which were loaded into the developed tool in order to calculate the savings potential.

Phase Size	17 ½"	12 ¼"	8 ½"
P(x)	50	50	50
Best Model Rotating	Pearson 6	Wakeby	Johnson SB
Rotating ROP ft/h	15.5	46	33
Rotating ROP m/h	5	14	10
Best Model Sliding	Johnson SB	Weibull	Weibull
Sliding ROP ft/h	55	60	60
Sliding ROP m/h	17	18.3	18.3

Table 13. Optimal Theoretical ROP and Best Fit Model for Different Phases

In order to prove the concept of the DSE and how it is related to ROP, the cross plot between the DSE and ROP has been generated for the all phases. Figure 43 shows the cross plots of DSE and ROP 17 1/2"Phase. The plot clearly indicates the correlation between the DSE and ROP, low ROP is always corresponding to high DSE and vice versa.

Causing low ROP can be one of the factors which have a direct link to the ROP and DSE. Therefore in order to identify the factors which were behind the low ROP the other cross plots are necessary.

From Figure 45 and 46 we deduct the following.

- When WOB was increased beyond 14000 Ibf, the ROP declined to be less than 40 ft/hr [The flounder point].
- DSE kept increasing with WOB.
- Low WOB generated low ROP and DSE.
- When TOB was increased the ROP reduced whereas DSE was increased correspondingly.
- The histograms of the WOB and TOB show that 50% of their values for both of them are in the ranges which cause low ROPs.
- The linear relation between WOB and surface torque is clearly shown in the cross plot chart Figure 47.
- Increasing WOB leads to high TOB, high DSE and low ROP.

The main idea of plotting the ROP versus DSE is to demonstrate that ROP can be improved and the target ROPs can be reached in future wells if the drilling parameters are optimized based on the concept of DSE and by real time surveillance of DSE[8].Next section explains in more details about the reasons for having low ROP and how they are linked to DSE.
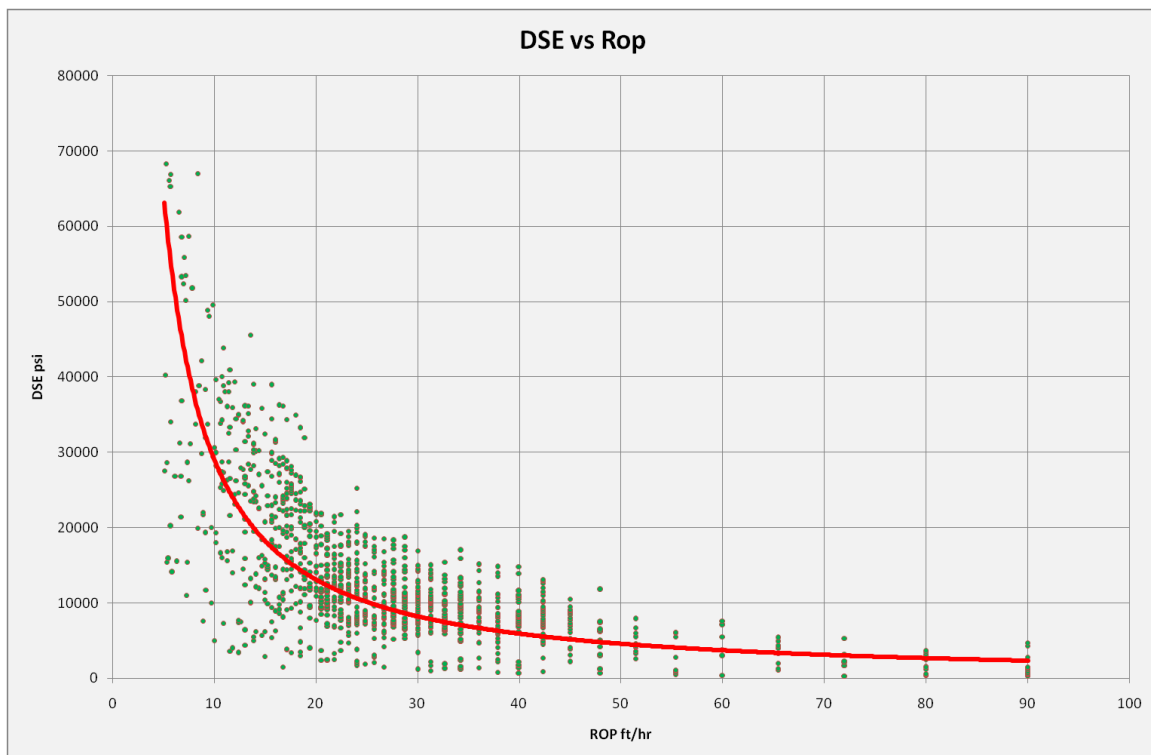
Figure 43. Cross Plots of DSE and ROP 17 1/2" Phase
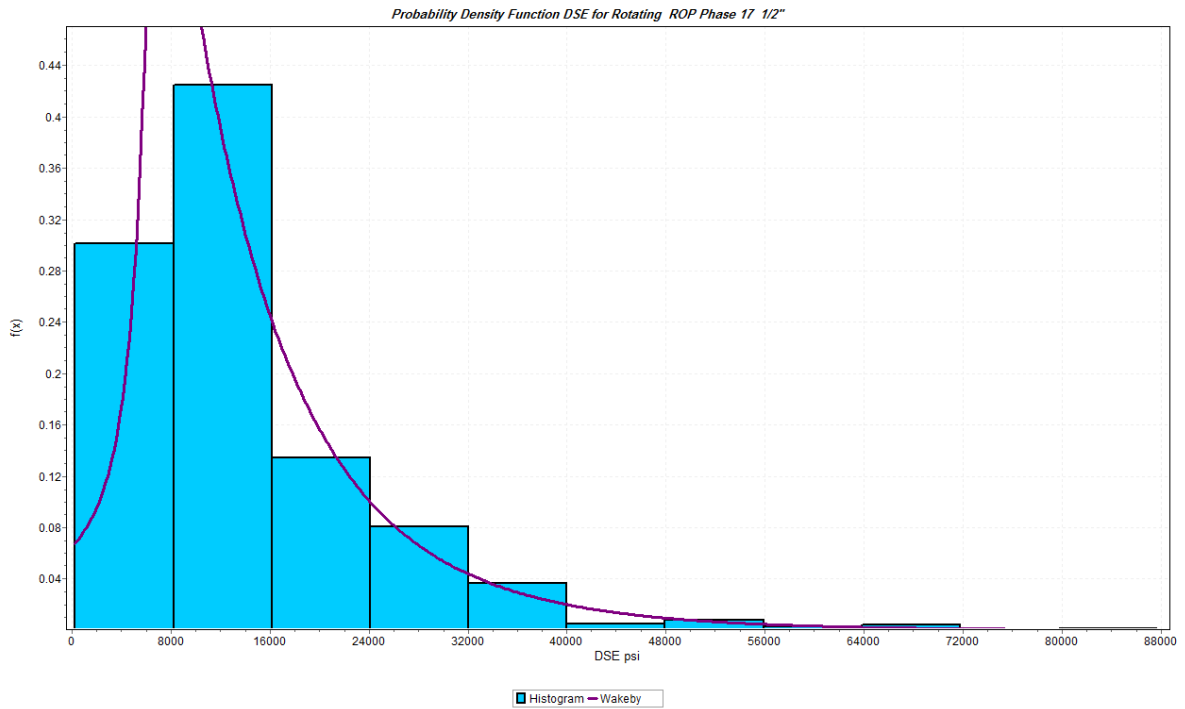
Figure 44. Probability Density Function of DSE for 17 ½" Phase
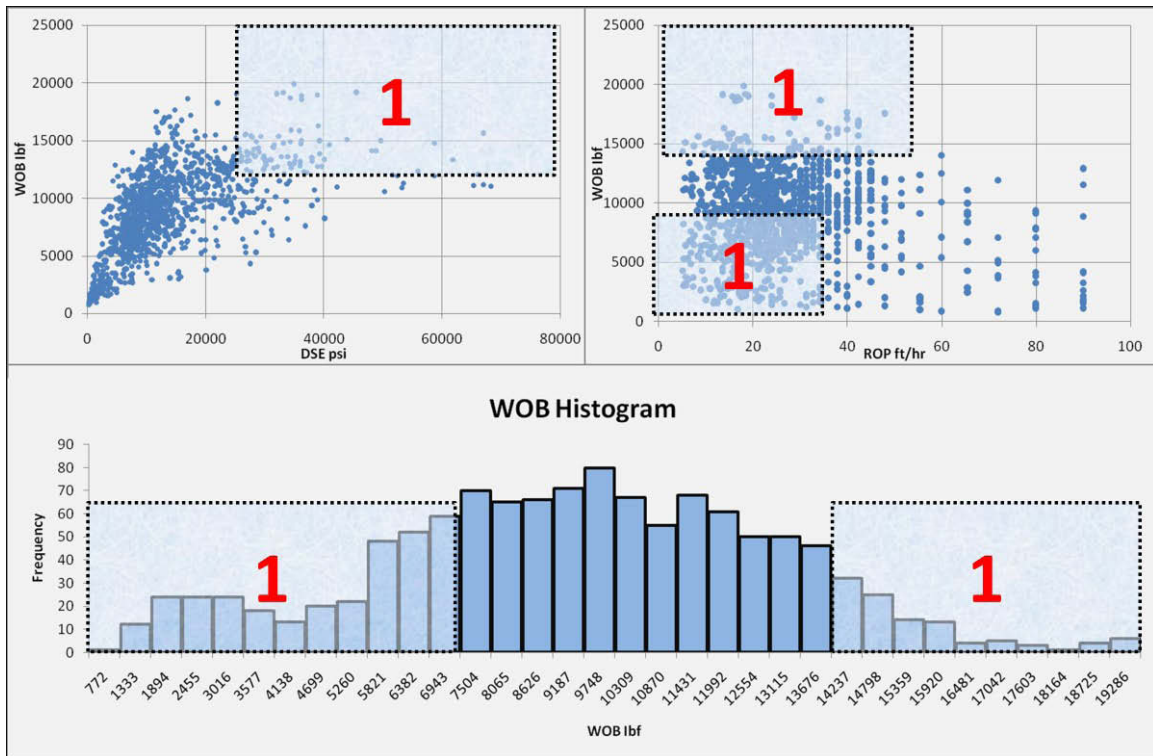
Figure 45. WOB versus [ROP & DSE] and WOB Histogram for 17 ½" Phase
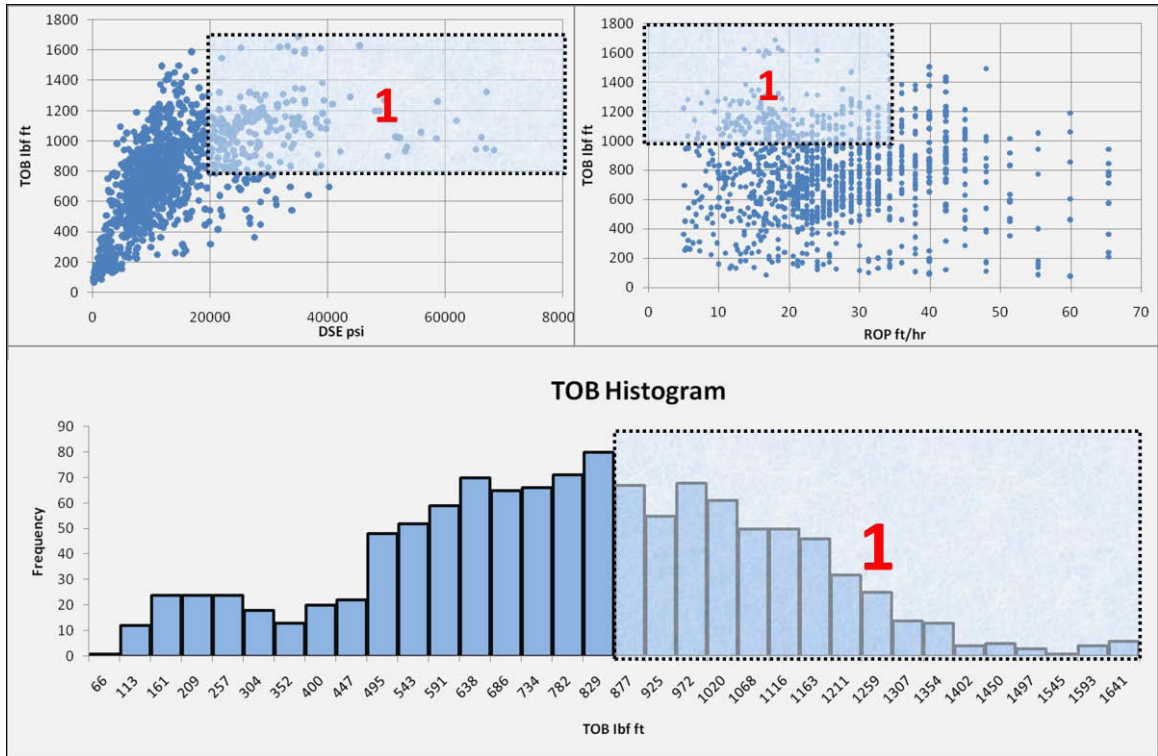
Figure 46. TOB versus [ROP & DSE] and TOB Histogram for 17 ½" Phase
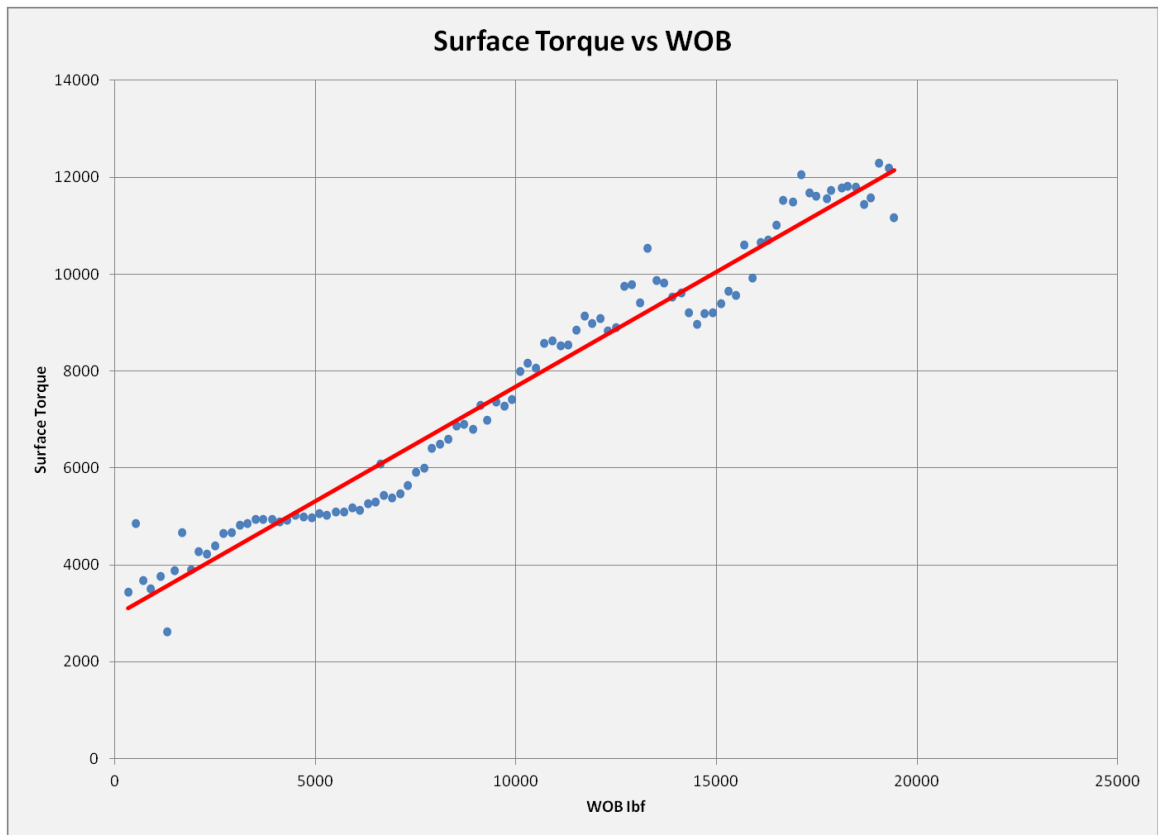
Figure 47. Cross Plots of WOB and Surface Torque Well 1 17 1/2" Phase

5.4.4. Enhancing the Understanding of Reasons for Low ROP in Different Formations

Using the concept of DSE the second part of this study was conducted to identify and explain the causes of low ROP in different formations.

By focusing on ROP and DSE versus depth trends we can easily point out that the decline of ROP could be rapid or dramatic. The rapid drop of the ROP might been caused by factors which are out of the central focus of this study such as bit balling, bit dulling and vibration. Therefore only the dramatic drop will be highlighted and described.

Four different formations have been encountered while drilling the wells, the following paragraphs describe them.

Silesian Nappe

Represented by stratal sequence the Těšín-Hradiště Formation - fine-rhytmic flysch sedimentation of dark grey, calcareous silstones and claystone with sequences layers of the Hradiště Sandstones and Conglomerates and rarely is accompanied by the teschenite volcanic association (teschenit, picrite, diabase).

Subsilesian Nappe

represented by dark (less frequently variegated) calcareous silstones and silty-sandy claystones with a varying portion of sandy laminae and randomly cumulated beds of calcareous sandstone having thickness of cm up to 2 m.

Pelitic Facies

Represented by very fine-grained greenish-grey calcareous claystones/ siltstones with sandy laminae.

Basal clastics

Represented by calcareous sandstones and fine-grained conglomerates

In order to make the data comprehensively readable, the data of the four wells has been plotted in one chart for the different formations.

5.4.4.1.   Silesian Nappe

Region NO.1

The steady reduction on ROP at this zone obviously caused by WOB, the other factors do not have influence since they stay stable.

From Figure 46 we can see that the WOB was gradually raised as drilling was in progress and average ROP was around 40 ft/hr, suddenly the DSE started to increase as WOB increased further. When the WOB got to 14500 Ibf [Point 1] the ROP declined mean while the DSE increased. The main conclusion which can be drawn out is that the Flounder point reached when WOB was between 12000 and 13000 Ibf. However, the driller kept increasing the WOB that caused reduction on ROP.

Region No.2

Here we can talk about two ranges, first one starts from 738 ft till 966 ft, and the low ROP here is due to the fluctuations of the total RPM whereas the main causes of the ROP reduction in the second range are inefficient bit hp and WOB.

In the first range the driller increased the WOB rapidly in order to increase the ROP but it did not help , it caused the DSE to increase and sharply reduced the ROP.
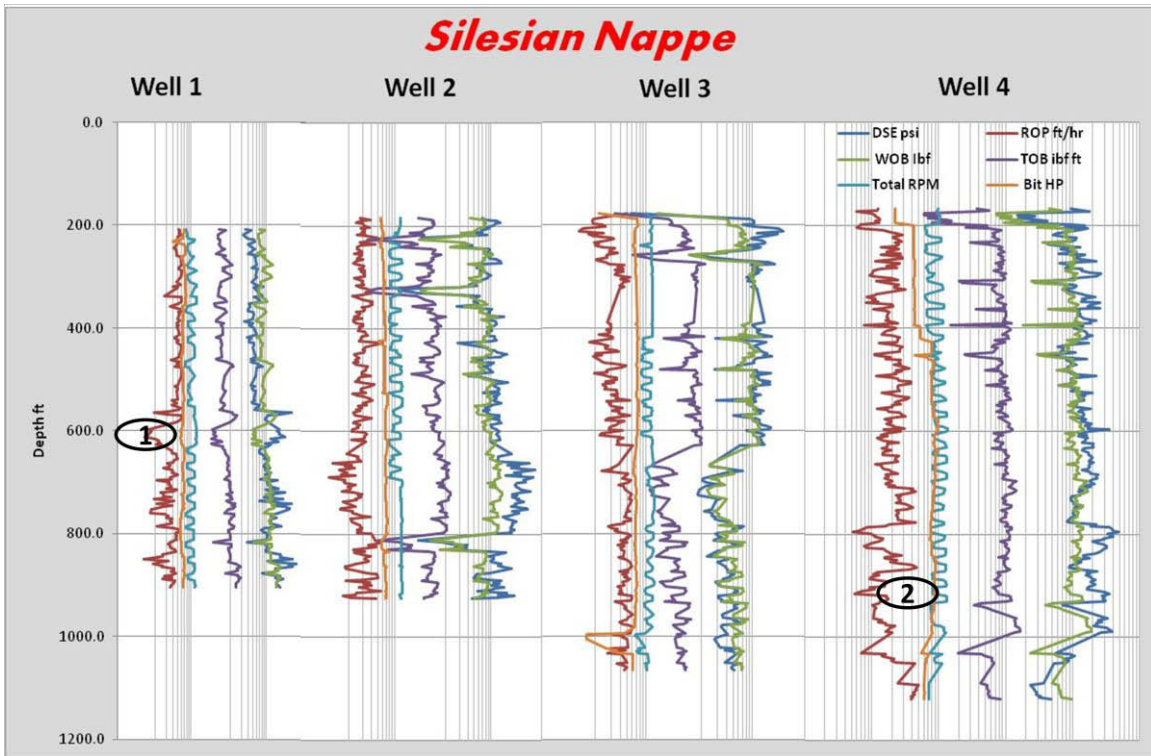
Figure 48. Drilling Parameters (DSE, WOB, Total RPM, TOB, ROP and Bit hp) versus Depth
for Silesian Nappe Formation
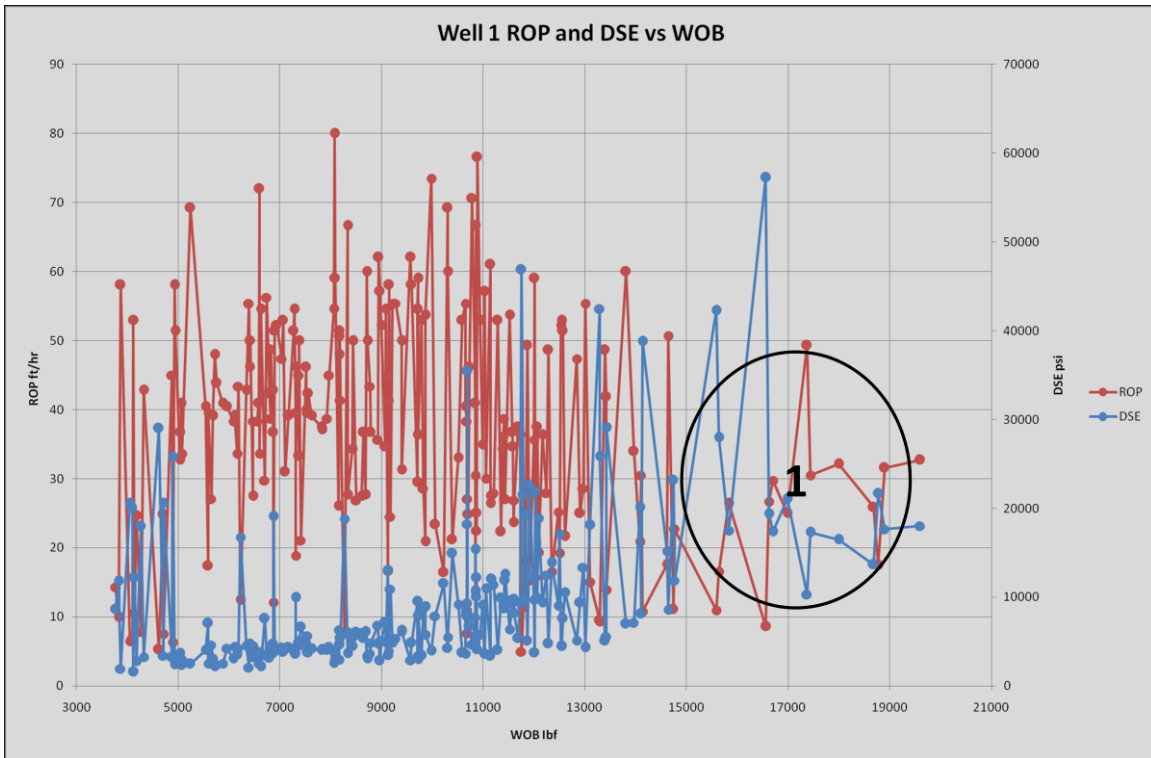
Figure 49. Well 1 ROP and DSE versus WOB Silesian Nappe Formation

5.4.4.2. Subsilesian Nappe

Region NO.1

The reason of having low ROP here is the intermittent increases of TOB.

Region NO.2

High TOB causes the reduction on the ROP here too although the driller increased the WOB to improve the ROP.

Through modifying point 2 [Figure 48], it is easy to see how the TOB was dramatically increasing, the ROP was not stable and once the WOB got to around 13000 Ibf the ROP went down and was stable around 20 ft/hr.

The drilling tried to modify the ROP by keeping increasing the WOB , that increase in WOB did not overcome the torque consequently the ROP kept declining.
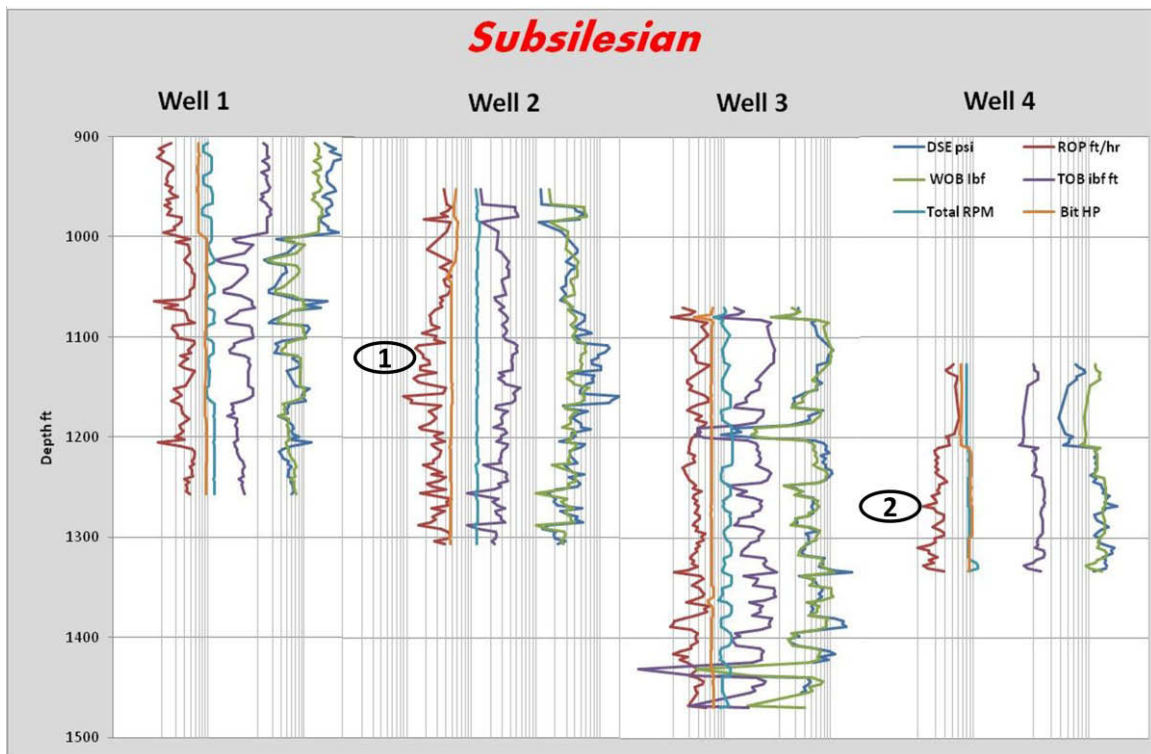
Figure 50. Drilling Parameters (DSE, WOB, Total RPM, TOB, ROP and Bit hp) versus Depth for Subsilesian Nappe Formation
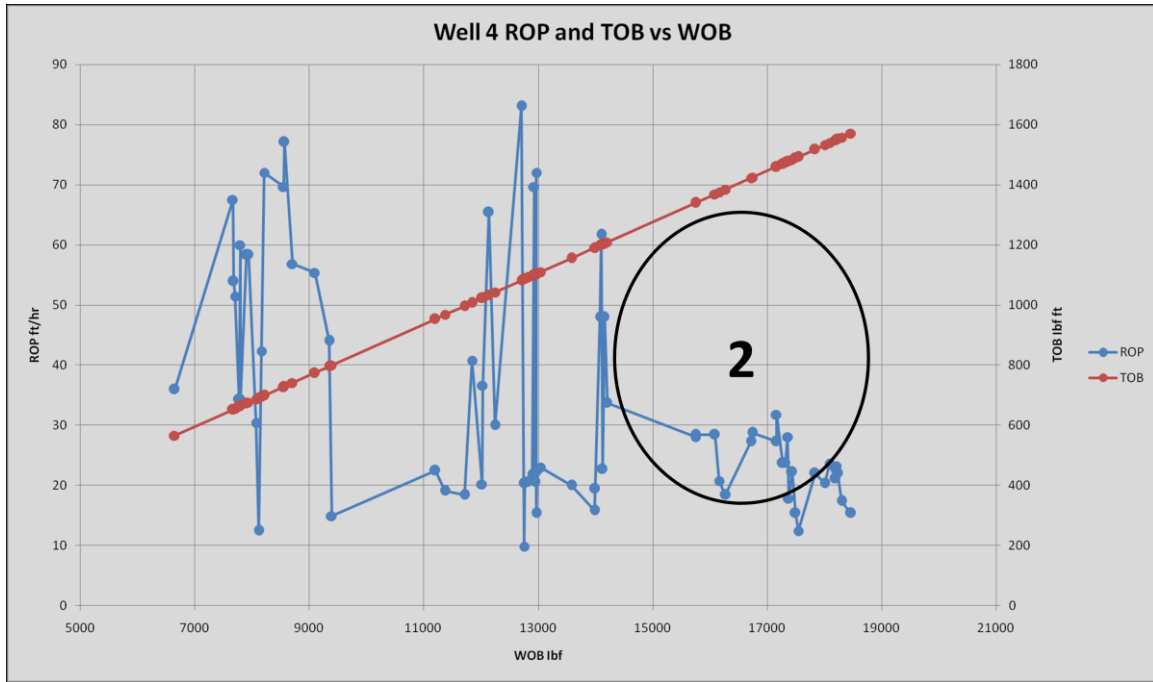
Figure 51. Well 4 ROP and TOB versus WOB Subsilesian Nappe Formation

5.4.4.3. Pelitic Facies

Region NO.1

Generally the cause of low ROP here is the total RPM, it seems as that the driller was looking for the flounder point.

WOB and RPM are the two variable parameters that can be controlled by the drillers and enhance the drilling efficiency. Point 1 in Figure 50 is the best example to demonstrate how the RPM significantly affects the ROP.

We see that the ROP was quite high and when RPM declined from 120 to 90 correspondingly the ROP reduced from 40 to 10 although the driller increased the WOB to increase the ROP, once he increased the RPM the ROP raised again.
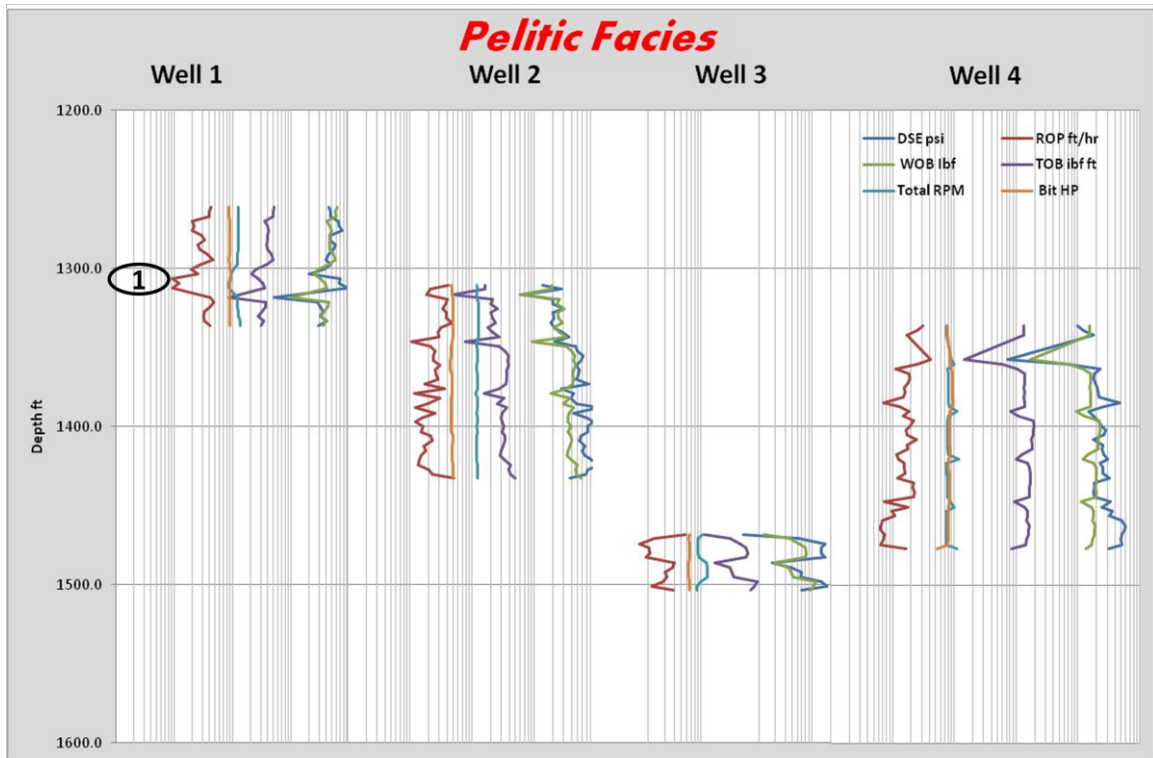
Figure 52. Drilling Parameters (DSE, WOB, Total RPM, TOB, ROP and Bit hp) versus Depth for Pelitic Facies Formation
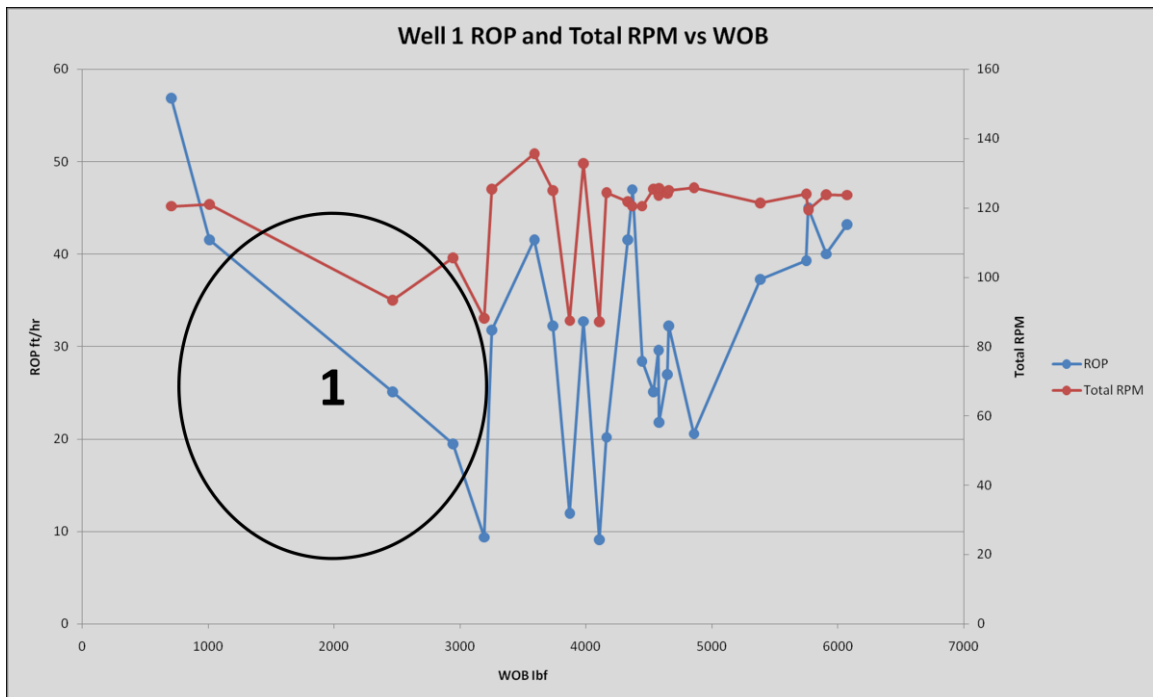
Figure 53. Well 1 ROP and Total RPM versus WOB Pelitic Facies Formation

5.4.4.4. Basal clastics

Region NO.1

Significant reduction on the ROP caused by the sharp decline of the bit hp, bit hp reduced from 90 to 3.

The bit hp could be the main driver to move from an inefficient to a efficient drilling when the other parameters are constants.

Region NO.2

Again inefficient RPM is the main dominant here
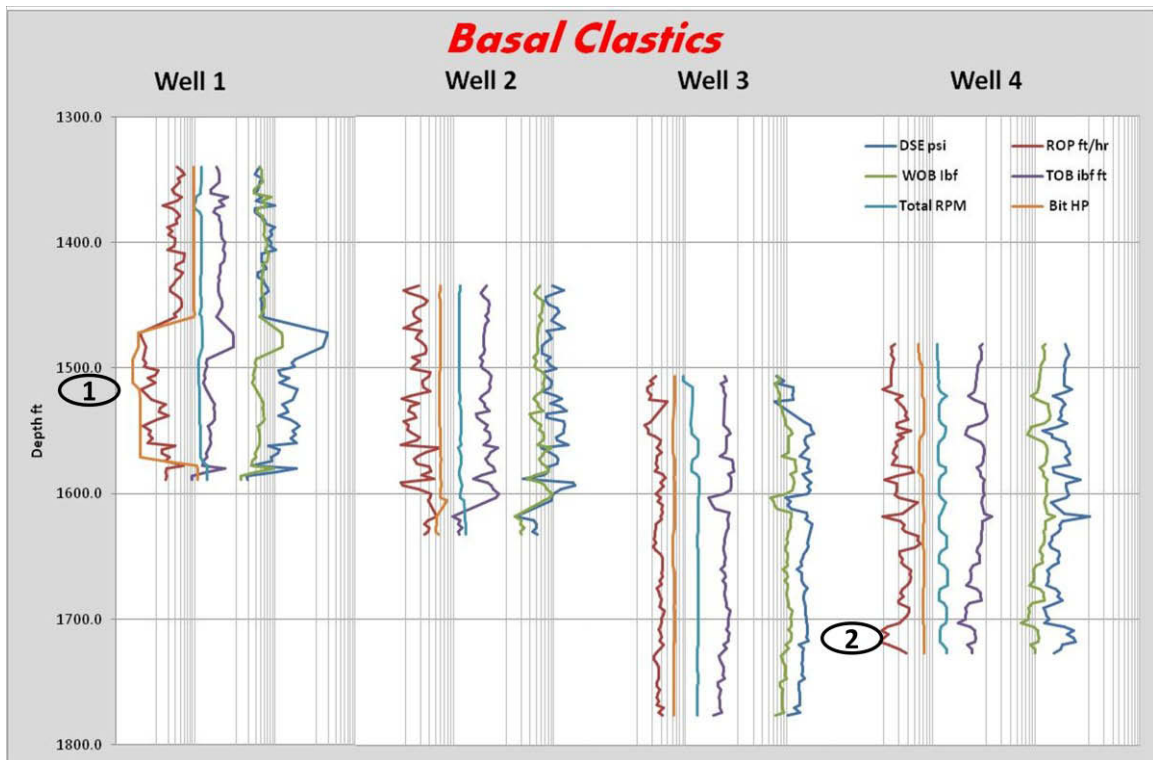
Figure 54. Drilling Parameters (DSE, WOB, Total RPM, TOB, ROP and Bit hp) versus Depth for Basal clastics Formation

5.5. Post Analysis Performance

The following charts are self explanatory and they outline that just by focusing on routing drilling operation and optimizing rate of penetration there will be potential saving of 15 and 13 days for Rig A and B respectively.

NPT makes up 13% of the total Rig A time whereas it makes up approximately 20% of the total Rig B time. Through looking deeply into trouble time analysis charts for both rigs we can point out that waiting in general is considered to be relatively high, it presents 30% and 20% of the total NPT for Rig A and B respectively.
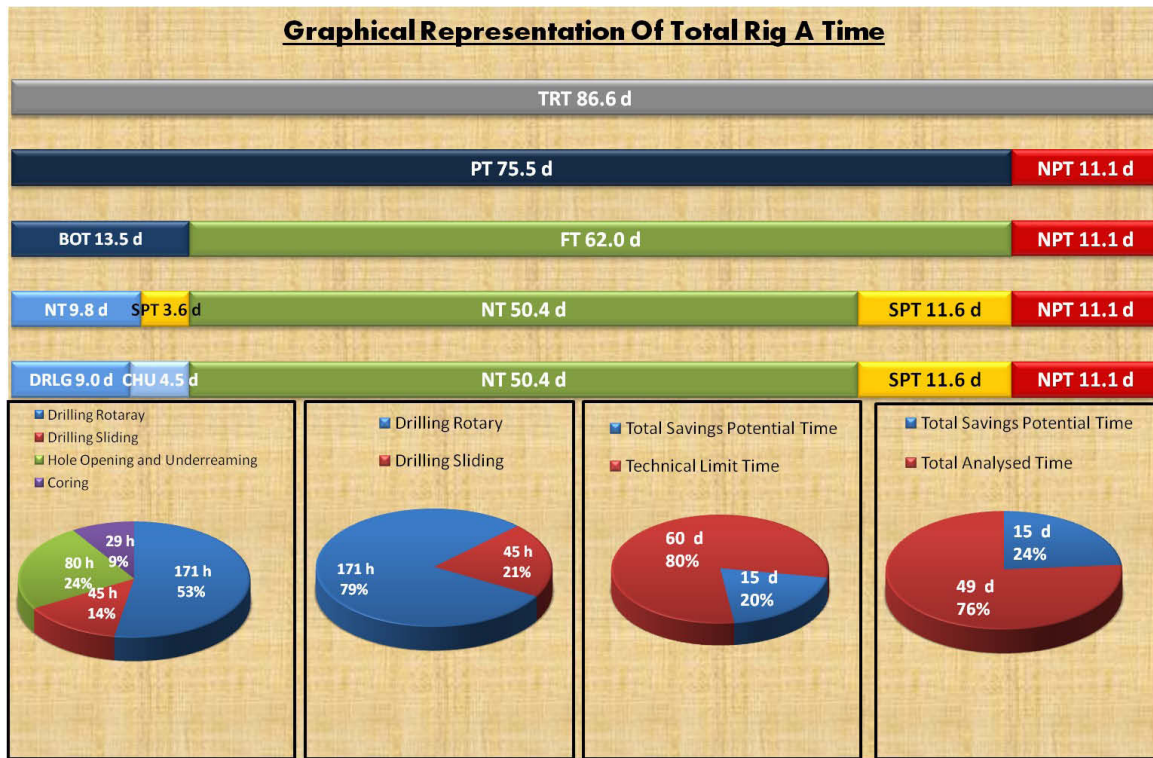
Figure 55. Post Analysis Total Time Breakdown Rig A
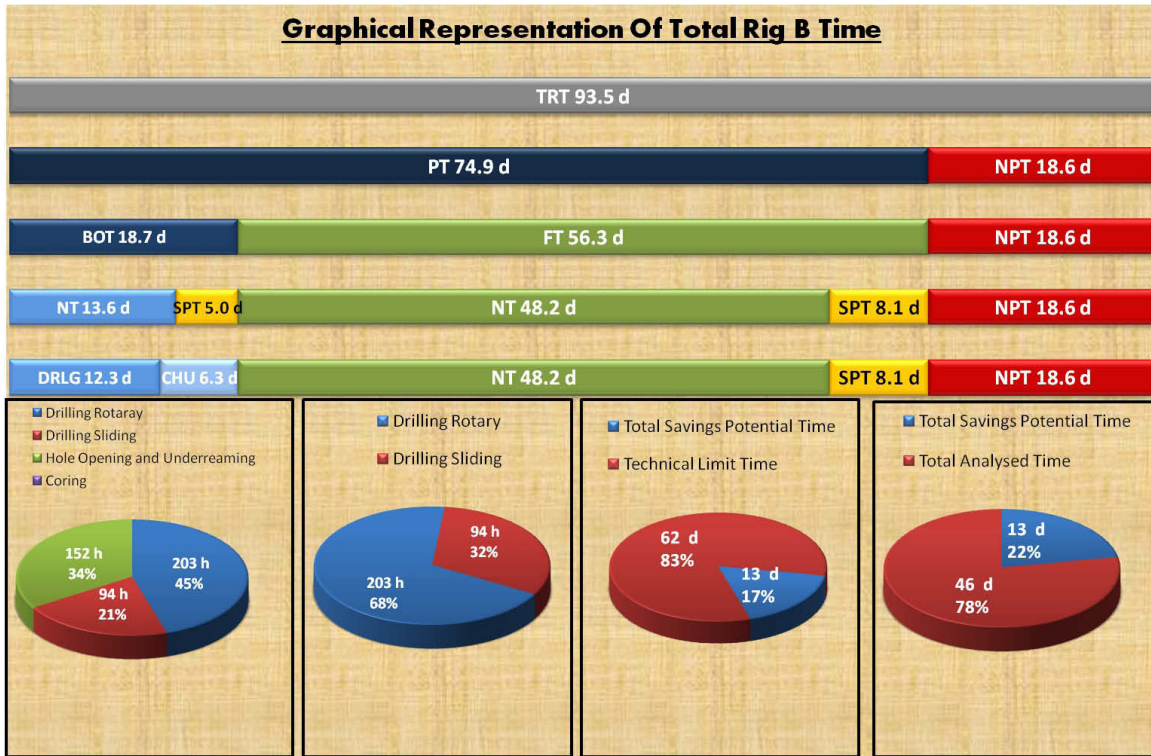
Figure 56. Post Analysis Total Time Breakdown Rig B
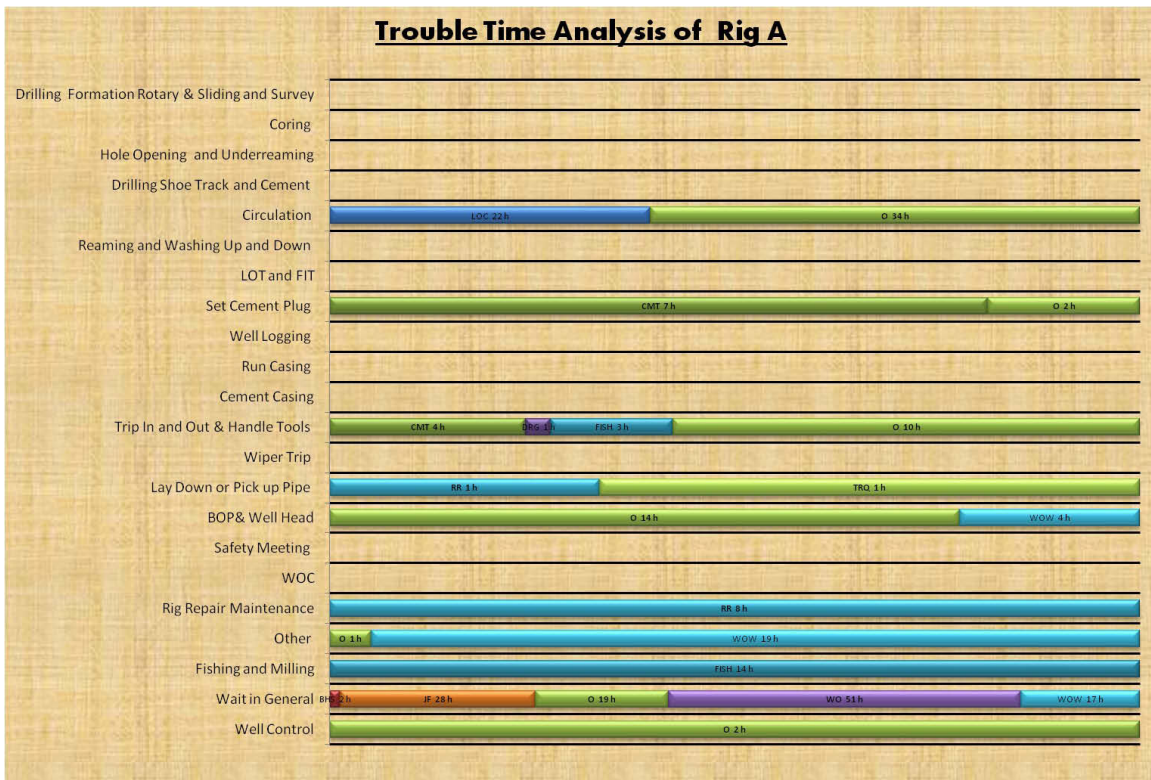
Figure 57. NPT Breakdown Rig A
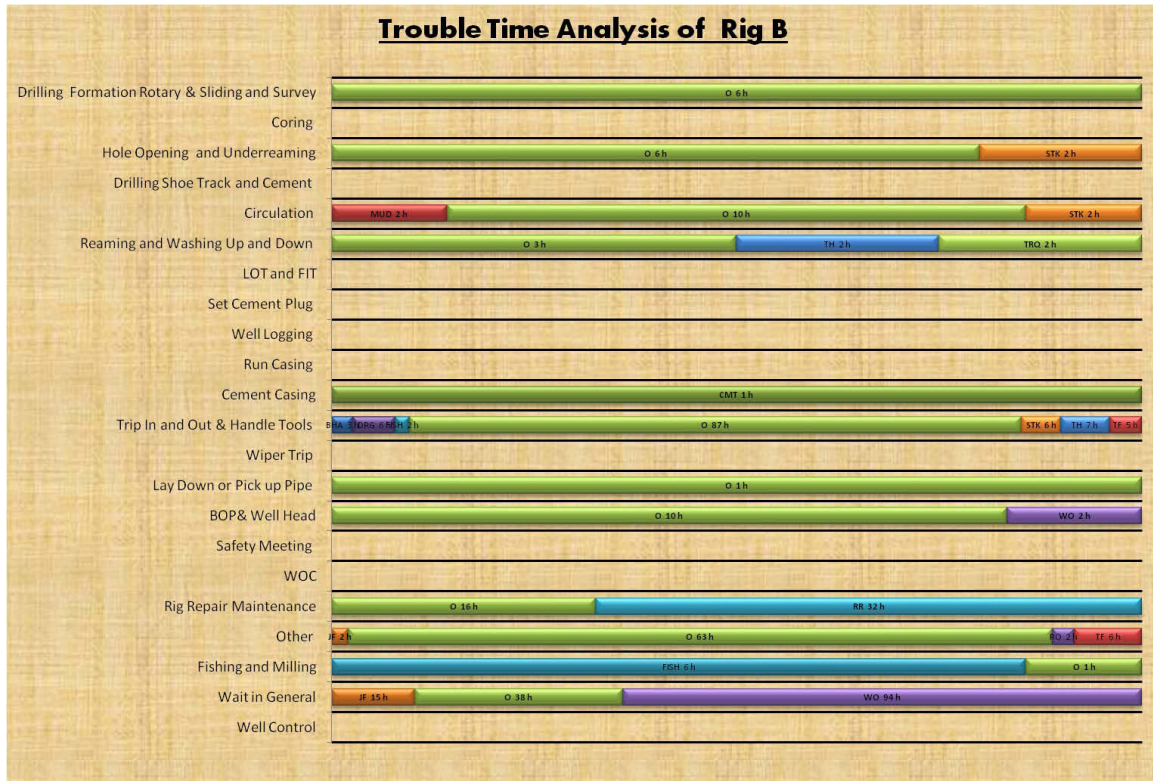
Figure 58. NPT Breakdown Rig B

5.6. Case Study Conclusions

Based on this work the following conclusions can be made:

- The overall performance of both rigs is relatively equal.
- Well#3 is considered to be the reference well therefore it can be used as a guide for the future planning. Moreover phases break down offers a widespread source of information to plan for new wells.

- Concerning time consumption, tripping in and out [20%] make a large percentage of overall well construction time, followed by BOP and Wellhead Work [12%] as well as drilling [12%].

- Drilling sliding time presents up to 30% of the total drilling time which is considerably high.

- Savings potential time makes up 22% of the total analyzed data and up to 20% of the total technical limit time.

- Turning the BCT of the tools for the special KPIs increases the savings potential to be as high as 17 and 14 days for Rig A and B respectively.

- Savings Potential is even higher if operations are expanded to all rig operations (flat times).

- Implementation of the drill of test helps to increase the drilling efficiency and consequently reduce the drilling time and cost.

- Improving rig (crew) operations consistency will lead to savings.

- Through looking deeply into phases operations break down it would be possible to identify the true critical path eliminating unnecessary operations.

- The second part of analyzing the ROP of this study would be invaluable if gamma ray trends were added.

- The hidden lost time of the routine drilling operations makes up approximately 40% of the overall savings potential, thus it is strongly recommended to investigate about the tools in use and try to improve them.

- DSE concept helps to identify the reasons of having low ROPs and to improve the ROPs in future drilling.

- The study shows that ROPs can be improved and the target ROPs can be reached in future wells if the drilling parameters are optimized based on the concept of DSE and by real time surveillance of DSE.

6. Conclusions and Recommendations

6.1. Conclusions

For the purpose of effective drilling performance measurement and drilling efficiency evaluation it is necessary to utilize every single bit and pieces of the data that generated during the drilling operations whether is meta data or sensor data.

Drilling operations are sorted using different activity breakdown, each activity has the potential to be individually measured, evaluated, and optimized by using the existing methods and approaches. Nevertheless idealistic overall drilling performance measurement and evaluation requires the contribution of all individuals, therefore the scope of this thesis was to develop a concept for a software too that utilizes and combines the output results of different approaches and methods. The tool effectively and easily allows the drilling engineers analysing and tracking the operations of multiple rigs and services companies. Moreover it is capable to recognise the savings potential from non automatically detected operations.

Since the graphical analysis is always preferable hence the tool generates multiple charts, these charts collectively are comprehensive and readable that leads to valuable analysis.

In order to demonstrate the validation and proof the concept of the developed tool an actual data set was loaded and analysed. The output charts help to identify the overall savings potential, indicate the potential areas of improvement and highlight the tasks that can be eliminated or significantly reduces in duration. In addition, it offers a widespread source of information to plan new wells; in general it covers nearly all aspects related to performance measurement and evaluation. The case study always proves the concepts of DSE and shows the correlation between the DSE and ROP.

6.2. Recommendations

Based on the findings of this thesis the following recommendations can be drawn:

- The only coding system recognized by the tool is Genesis 2000 thus in order to make the tool globally in use more coding systems should be Included.

- The tool is built on Microsoft excel therefore time required by the tool to import and process the data is the most shortcoming recognized up to date to overcome it is recommended to build it on proven software that will allow faster development, less time and unlimited data storage.

- Improve ADPM tool so that it be able to differentiate between productive and non productive time, in addition to include all different savings potentials in the final savings potential report.

- Coding of the drilling activities is prone to have human errors, such errors cause bad analysis results. Therefore it is necessary to crosscheck the codes prior importing the data into the tool.

- Improve the tool so that it creates a ideal time estimate for the future wells.

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Nomenclature

DDR   Daily Drilling Report

ROP   Rate of Penetration

TLT   Technical Limit Time

ILT   Invisible Lost Time

LT   Lost Time

BHA   Bottom Hole Assembly

ADPM   Automated Drilling Performance Measurement

KPIs   Key Performance Indicators

MSE   Mechanical Specific Energy

Ab   Bit Area in^2

Db   Bit Diameter in

RPM   Revolutions per Minute

TOB   Torque on Bit ft-Ibf

WOB   Weight on Bit Ibf

μ   Bit Specific Coefficient of Sliding Friction Dimensionless

hpb   Bit hydraulic Horse Power

ʎ	Bit Hydraulic Factor Dimensionless
ρ	Mud Weight
FR	Flow Rate
TFA	Total Flow Area of the Bit Nozzles
Δp bit	Pressure drop across the bit
hp	Horsepower
HSI	Bit Performance Hp/in^2
UCS	Rock Unconfined Compressive Strenght
BCT	Best Composite Time

Appendix A

Coding of the Drilling Activities which are recognized by the Developed Software (Gnesis Coding System)

Phase Codes

- ❖ **PS – Pre-spud**. Includes all operations that occurs prior to drilling the hole, examples when building up the first bottom hole assembly [BHA], mixing the spud mud.
- ❖ **Different hole size from 1" to 45"** . Includes all the phases between the prespud and end of well. The name of the well phases always related to the hole sizes. Making up BHA for drilling new formations and breaking down BHA once the total depth has been reached are the starting and ending points of a particular phase respectively.
- ❖ **EOW - End Of Well**. A starting point of the end of the well phase is a company individual decision; most of the companies apply EOW once the well has reached the total depth in this case the EOW phase may include major operations such as logging, run casing, running completion, other companies use it once the well head has been installed in this case it includes only the cleaning activities.

Class Codes

- ❖ **Planned operations [PD - Planned Drilling, .PE - Planned Evaluation, PC - Planned Completion]**. They are all the operations that have been preplanned and considered money and time.
- ❖ **Trouble operations [TD - Trouble Drilling, TE - Trouble Evaluation, TC - Trouble Completion].** include all unplanned operations and all the encountered troubles.

Major Operation Codes

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Operation Codes

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

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

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

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

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

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

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

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

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

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

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

- ❖ **DHO - Drilling Hole Opening /Underreaming**. Includes opening or under-reaming a pilot hole.

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

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

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

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

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

- ❖ **LDP - Lay Down Pipe**. Includes laying down/pick up and rack back HWDP/ Drillpipe.

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

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

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

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

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

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

- ❖ **POV - Position Offshore Vessel**. Includes Positioning rig to be in drilling position.

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

- ❖ **RD - Rig Down**. Includes Only rig down the rig.

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

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

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

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

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

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

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

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

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

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

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

❖ **WO - Wait On**. Includes time for operation suspended due to waiting for any thing till operation resumes as planned.

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

Trouble Codes

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

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

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

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

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

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

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

- ❖ **DRG – Drag**. Includes problems with drag. This code might be used as a problem indicator rather than lost time code.
- ❖ **DS - Drill String**. Includes lost time due to drill string failure [pipe wash out].
- ❖ **FISH – Fish**. Includes lost time due to fish in hole.
- ❖ **HC - Hole Cleaning**. Includes lost time due to hole cleaning problem.
- ❖ **JF - Job Failure**. Includes lost time due to Job Failure. I a job [test, completion] was run unsuccessfully NOT due too tools malfunction or damage or a hole problem.
- ❖ **LOC - Loss of Circulation**. Includes lost time due to loss of circulation.
- ❖ **MUD – Mud**. Includes lost time due to mud/hydraulic parameter.
- ❖ **NT - No Trouble**. Includes no trouble. This is a compulsory field and must be filled in the case of no trouble.
- ❖ **O– Other**. Includes lost time due to unlisted problems.
- ❖ **RO - Repair Other**. Includes lost time due to repairing service company's equipment.
- ❖ **ROP - Rate of Penetration**. Includes lost time due to low ROP [due to choosing wrong bit for formation, normally changing bit after only a few hours of drilling with new bit].
- ❖ **RR - Rig Repair**. Includes lost time due to rig repair.
- ❖ **S – Survey**. Includes lost time due to surveying [mis-run].
- ❖ **STK – Stuck**. Includes lost time due to pipe stuck.
- ❖ **TF - Tool Failure**. Includes lost time due to tool failure [downhole or surface], mainly service company tools, not used for BHA components other than logging and survey tools).
- ❖ **TH - Tight Hole**. Includes Lost time due to tight hole.
- ❖ **TRQ – Torque**. Includes lost time due to excessive torque.
- ❖ **WC - Well Control**. Includes lost time due to well control operation.
- ❖ **WO - Wait On**. Includes lost time due to well control operation.
- ❖ **WOW - Wait on Weather**. Includes lost time due to waiting on environmental conditions [weather or daylight].

Appendix B

Tripping Key Performance Indicators

- Tripping – Slip to Slip Connection Time [min].
- Tripping – Slip to Slip Connection Time - CH [min].
- Tripping – Slip to Slip Connection Time - OH [min].
- Tripping – Average Pipe Moving Speed [m/h, ft/h].
- Tripping – Average Pipe Moving Speed - CH [m/h, ft/h].
- Tripping – Average Pipe Moving Speed - OH [m/h, ft/h].
- Tripping – Pipe Moving Time [min].
- Tripping – Pipe Moving Time - CH [min].
- Tripping – Pipe Moving Time - OH [min].
- Tripping – Gross Running Speed [m/h, ft/h].
- Tripping – Gross Running Speed - CH [m/h, ft/h].
- Tripping – Gross Running Speed - OH [m/h, ft/h].
- Tripping – Gross Time per Stand [min].
- Tripping – Gross Time per Stand - CH [min].
- Tripping – Gross Time per Stand - OH [min].

Running Casing Key Performance Indicators

- Casing – Slip-to-Slip Connection Time [min].
- Casing – Slip-to-Slip Connection Time - CH [min].
- Casing – Slip-to-Slip Connection Time - OH [min].
- Casing – Pipe Moving Time [min].
- Casing – Pipe Moving Time - CH [min].
- Casing – Pipe Moving Time - OH [min].
- Casing – Average Pipe Moving Speed [m/h, ft/h].
- Casing – Average Pipe Moving Speed - CH [m/h, ft/h].
- Casing – Average Pipe Moving Speed - OH [m/h, ft/h].
- Casing – Gross Time per Stand [min].
- Casing – Gross Time per Stand - CH [min].

- Casing – Gross Time per Stand - OH [min].

- Casing – Gross Running Speed [m/h, ft/h].

- Casing – Gross Running Speed - CH [m/h, ft/h].

- Casing – Gross Running Speed - OH [m/h, ft/h].

- Casing – Gross Running Rate [joints/h].

- Casing – Gross Running Rate - CH [joints/h].

- Casing – Gross Running Rate - OH [joints/h].

Running BHA Key Performance Indicators

- BHA – Slip-to-Slip Connection Time [min].

- BHA – Pipe Moving Time [min].

- BHA – Average Pipe Moving Speed [m/h, ft/h].

- BHA – Gross Time per Stand [min].

- BHA – Gross Running Speed [m/h, ft/h].

Running Riser Key Performance Indicators

- Riser – Slip-to-Slip Connection Time [min].

- Riser – Average Pipe Moving Time [min].

- Riser – Average Pipe Moving Speed [m/h, ft/h].

- Riser – Gross Time per Stand [min].

- Riser – Gross Running Speed [m/h, ft/h].

- Riser – Gross Running Rate [joints/h].

Drilling Connection Key Performance Indicators

- Drilling – Weight to Weight Time [min].

- Drilling - Weight to Slips Time [min].

- Drilling – Slip to Slip Connection Time [min].

- Drilling - Slips to Weight Time [min].

- Drilling – Wellbore Treatment Time per Connection [min].

- Drilling – Circulating Time per Connection [min].

- Drilling – Reaming Time per Connection [min].

- Drilling – Washing Time per Connection [min].

Drilling Time per Stand Key Performance Indicators

- Drilling – Gross Time per Stand [min].

- Drilling – Gross Drilling ROP per Stand [m/h, ft/h].

- Drilling – Total Wellbore Treatment Time per Stand [min].

- Drilling – Total Circulating Time per Stand [min].

- Drilling – Total Reaming Time per Stand [min].

- Drilling – Total Washing Time per Stand [min].

- Drilling – Net Drilling Time per Stand [min].

- Drilling – Net ROP per Stand [m/h, ft/h].

- Drilling – Wellbore Treatment Time per Stand [min].

- Drilling – Circulating Time per Stand [min].

- Drilling – Reaming Time per Stand [min].

- Drilling – Washing Time per Stand [min].

- Drilling – Rotating Drilling Time per Stand [min].

- Drilling – Rotating Drilling Meterage per Stand [m, ft].

- Drilling – Rotating Drilling ROP per Stand [m/h, ft/h].

- Drilling – Sliding Drilling Time per Stand [min].

- Drilling – Sliding Drilling Meterage per Stand [m, ft].

- Drilling – Sliding Drilling ROP per Stand [m/h, ft/h].

Screen Key Performance Indicators

- Screen – Slip-to-Slip Connection Time [min].

- Screen – Slip-to-Slip Connection Time - CH [min].

- Screen – Slip-to-Slip Connection Time - OH [min].

- Screen – Pipe Moving Time [min].

- Screen – Pipe Moving Time - CH [min].

- Screen – Pipe Moving Time - OH [min].

- Screen – Average Pipe Moving Speed [m/h, ft/h].

- Screen – Average Pipe Moving Speed - CH [m/h, ft/h].

- Screen – Average Pipe Moving Speed - OH [m/h, ft/h].

- Screen – Gross Time per Stand [min].

- Screen – Gross Time per Stand - CH [min].

- Screen – Gross Time per Stand - OH [min].

- Screen – Gross Running Speed [m/h, ft/h].

- Screen – Gross Running Speed - CH [m/h, ft/h].

- Screen – Gross Running Speed - OH [m/h, ft/h].

- Screen – Gross Running Rate [joints/h].

- Screen – Gross Running Rate - CH [joints/h].

- Screen – Gross Running Rate - OH [joints/h].

Tubing Key Performance Indicators

- Tubing – Slip-to-Slip Connection Time [min].

- Tubing – Average Pipe Moving Time [min].

- Tubing – Average Pipe Moving Speed [m/h, ft/h].

- Tubing – Pulling Slip-to-Slip Connection Time [min].

- Tubing – Gross Time per Stand [min].

- Tubing – Gross Running Speed [m/h, ft/h].

- Tubing – Gross Running Rate [joints/h].

- Tubing – Gross Pulling Time per Stand [min].

- Tubing – Gross Pulling Speed [m/h, ft/h].

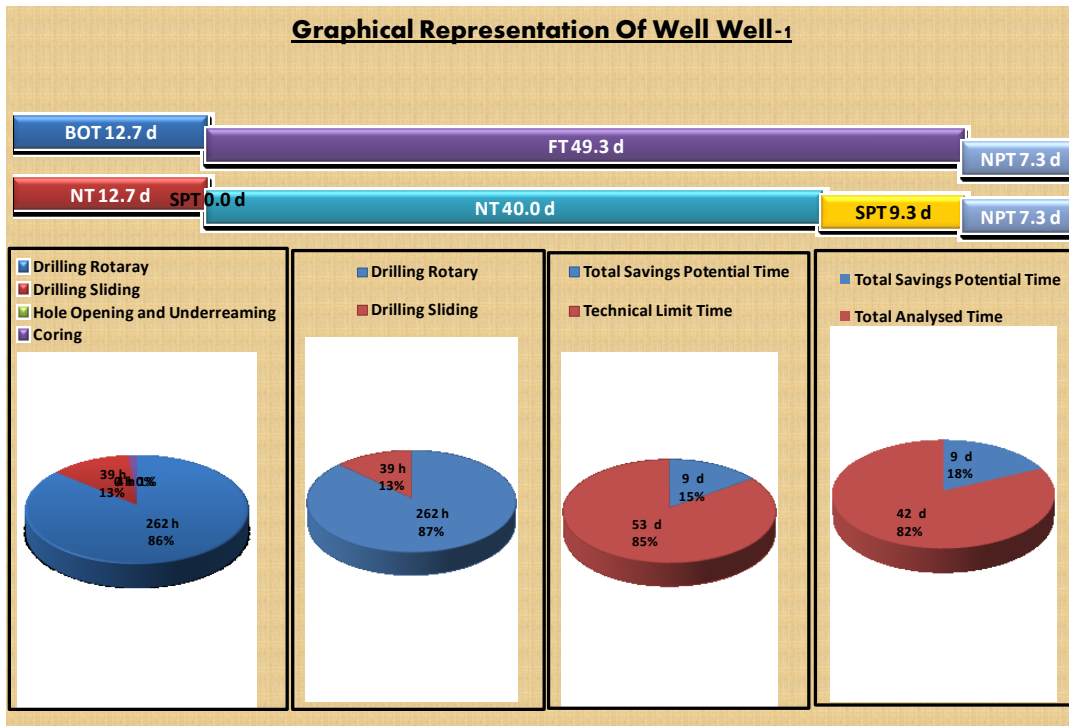- Tubing – Gross Pulling Rate [joints/h].

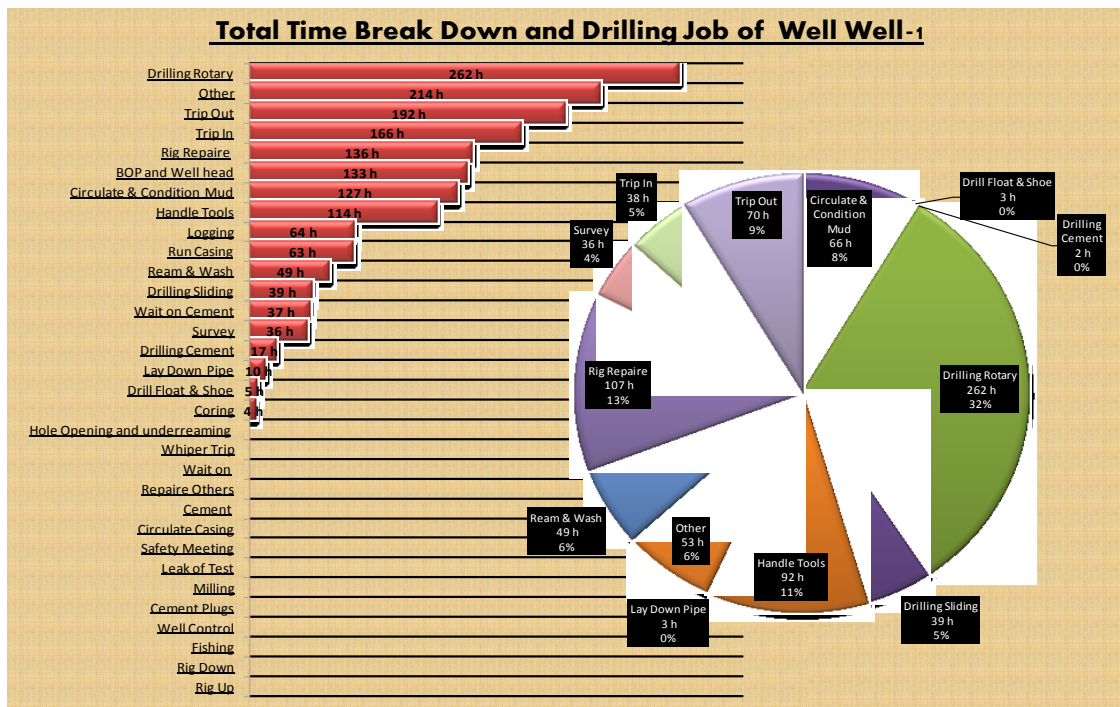# Appendix C

Figure 59. Well Total Time Analysis
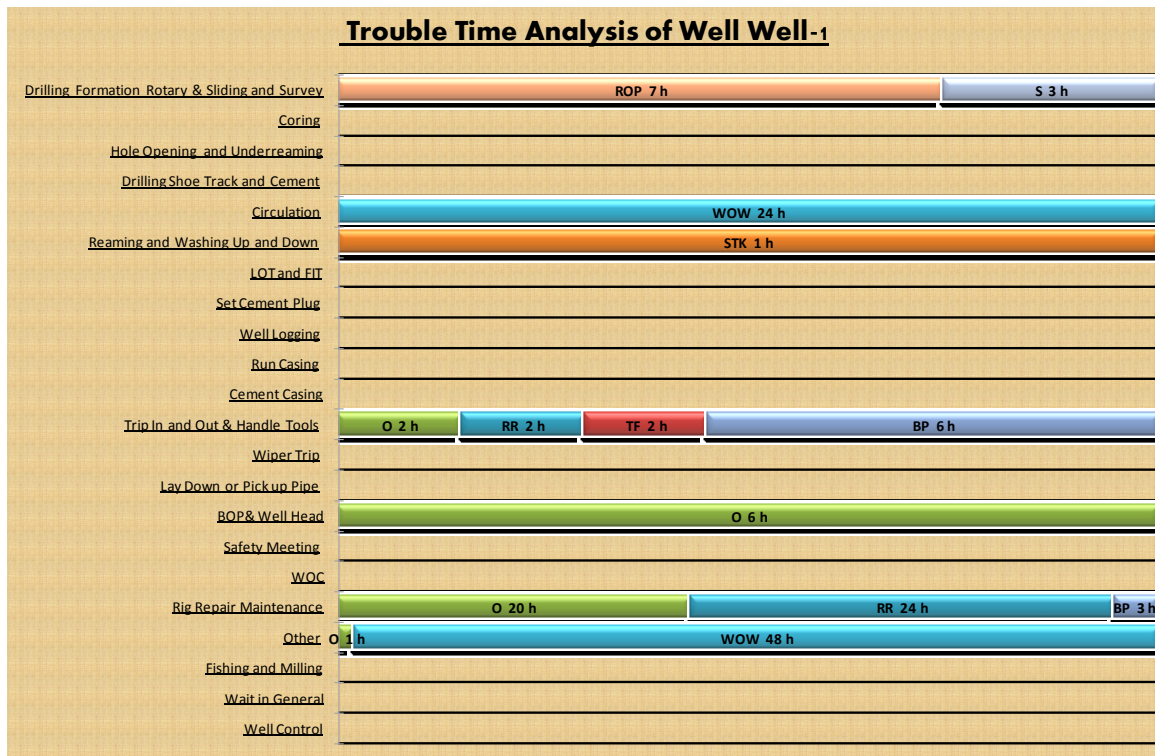

Figure 60. Well Total Time Break Down

Trouble Time Analysis of Well Well-1

Drilling Formation Rotary & Sliding and Survey	ROP 7 h / S 3 h
Coring	
Hole Opening and Underreaming	
Drilling Shoe Track and Cement	
Circulation	WOW 24 h
Reaming and Washing Up and Down	STK 1 h
LOT and FIT	
Set Cement Plug	
Well Logging	
Run Casing	
Cement Casing	
Trip In and Out & Handle Tools	O 2 h / RR 2 h / TF 2 h / BP 6 h
Wiper Trip	
Lay Down or Pick up Pipe	
BOP& Well Head	O 6 h
Safety Meeting	
WOC	
Rig Repair Maintenance	O 20 h / RR 24 h / BP 3 h
Other	O 1 h / WOW 48 h
Fishing and Milling	
Wait in General	
Well Control	

Figure 61. Well Total Trouble Time Analysis

Finaly Time Analysis of Well Well-1

Category	Initial Time	Non Productive Time	Savings Potential Time	Final Time
Drilling Formation Rotary & Sliding and Survey	336 h	10 h	36 h	290 h
Coring	4 h			4 h
Drilling Shoe Track and Cement	22 h			22 h
Circulation	127 h	24 h		103 h
Reaming and Washing Up and Down	49 h	1 h		48 h
Well Logging	64 h			64 h
Run Casing	63 h		10 h	53 h
Trip In and Out & Handle Tools	472 h	14 h	71 h	387 h
Lay Down or Pick up Pipe	10 h			10 h
BOP& Well Head	133 h	6 h	83 h	45 h
WOC	37 h		23 h	14 h
Rig Repair Maintenance	136 h	58 h		78 h
Other	214 h	64 h		150 h

Legend: Final Time, Savings Potential Time, Non Productive Time, Initial Time
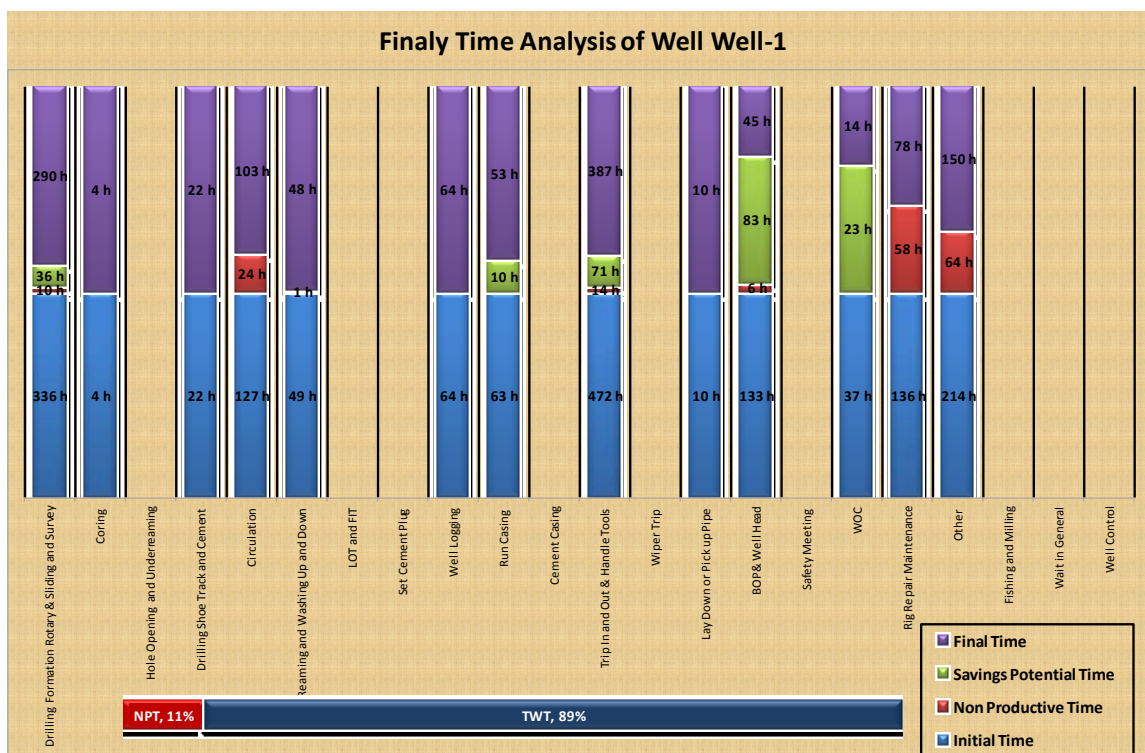
NPT, 11% — TWT, 89%
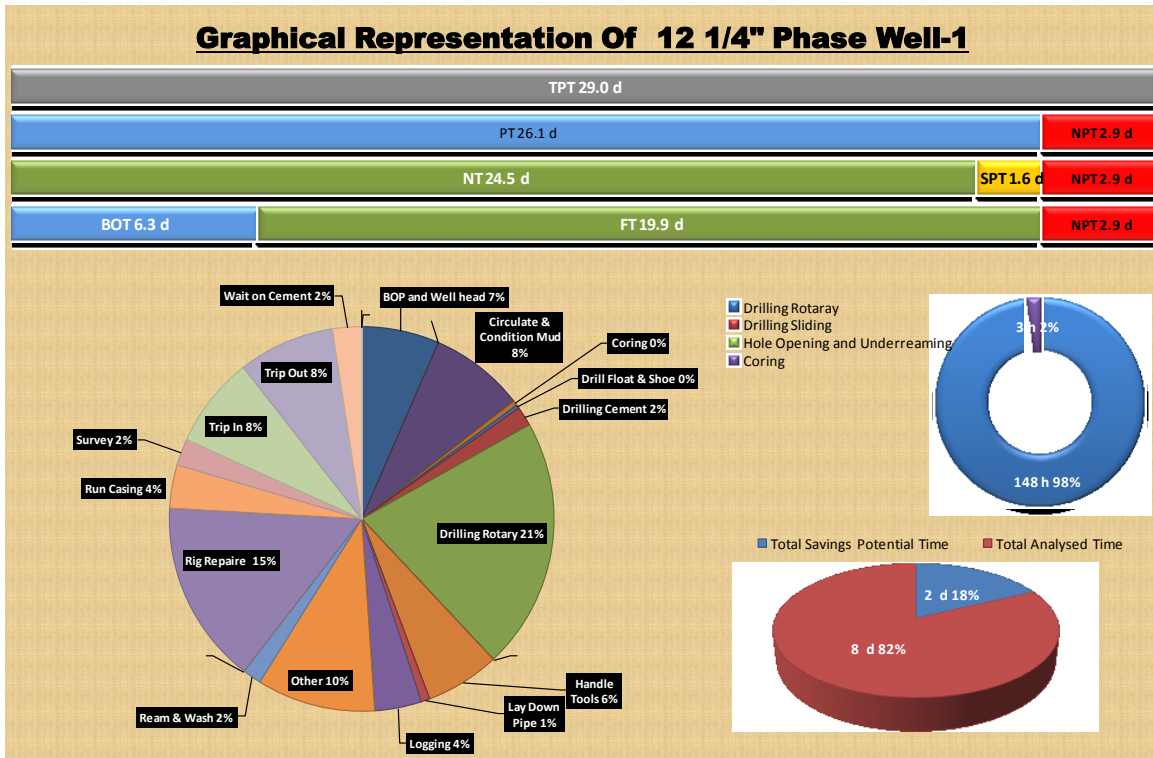
Figure 62. Well Final Analysis
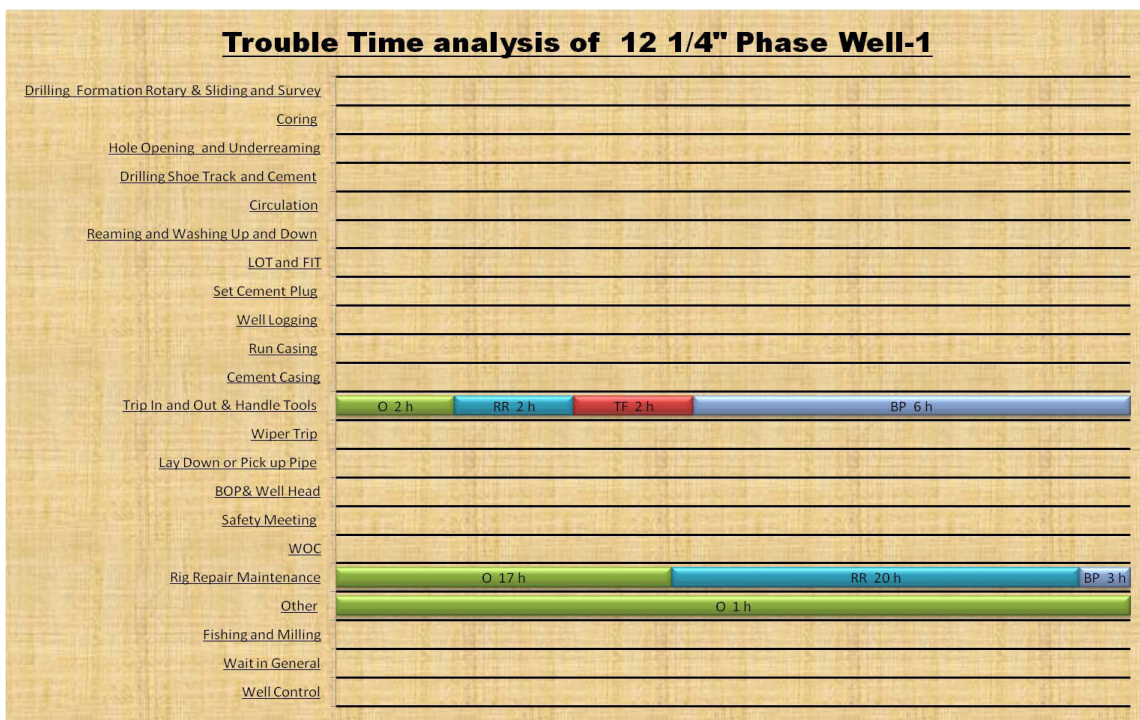
Figure 63. Phase Total Time Break Down

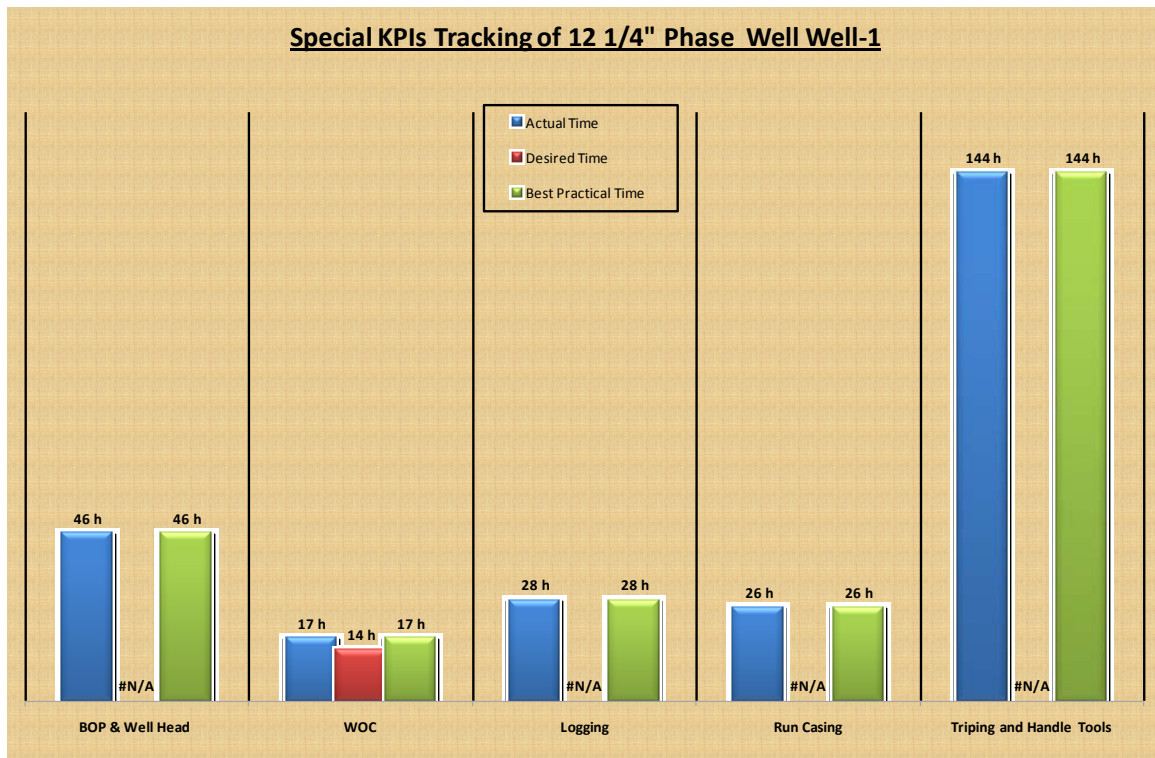Figure 64. Phase Total Trouble Time Analysis

Figure 65. Phase Special KPIs Tracking
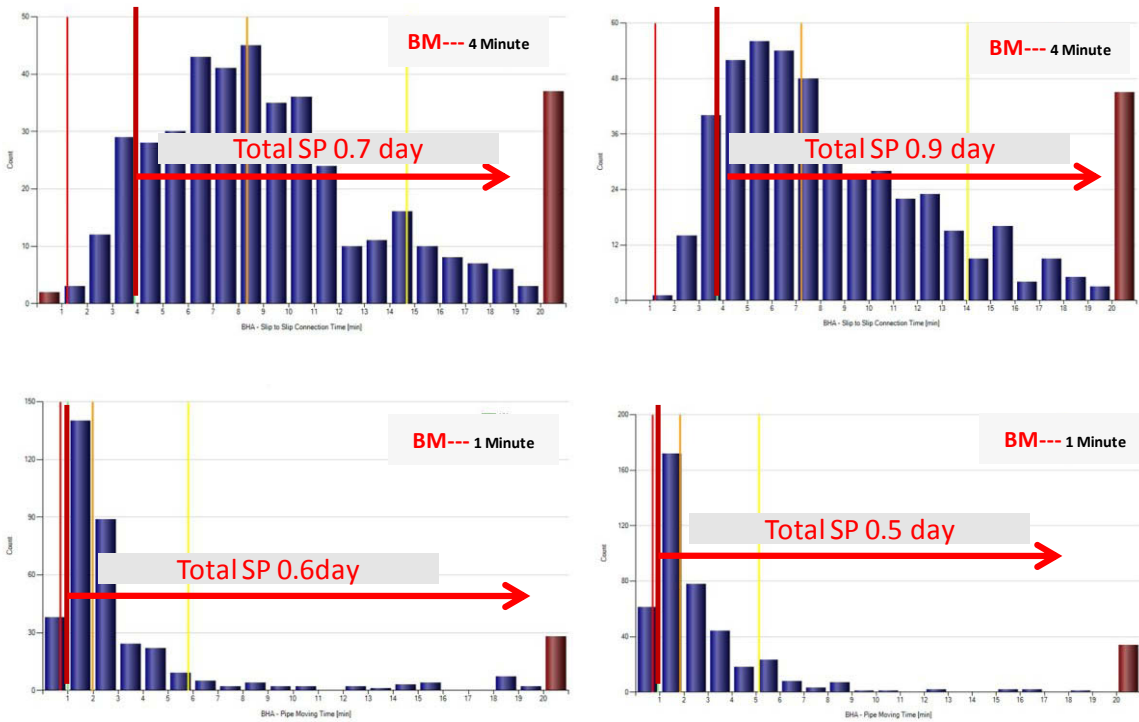
Appendix D

Figure 66. BHA Slip to Slip Connection and Pipe Moving Time Histogram for Rig A and B
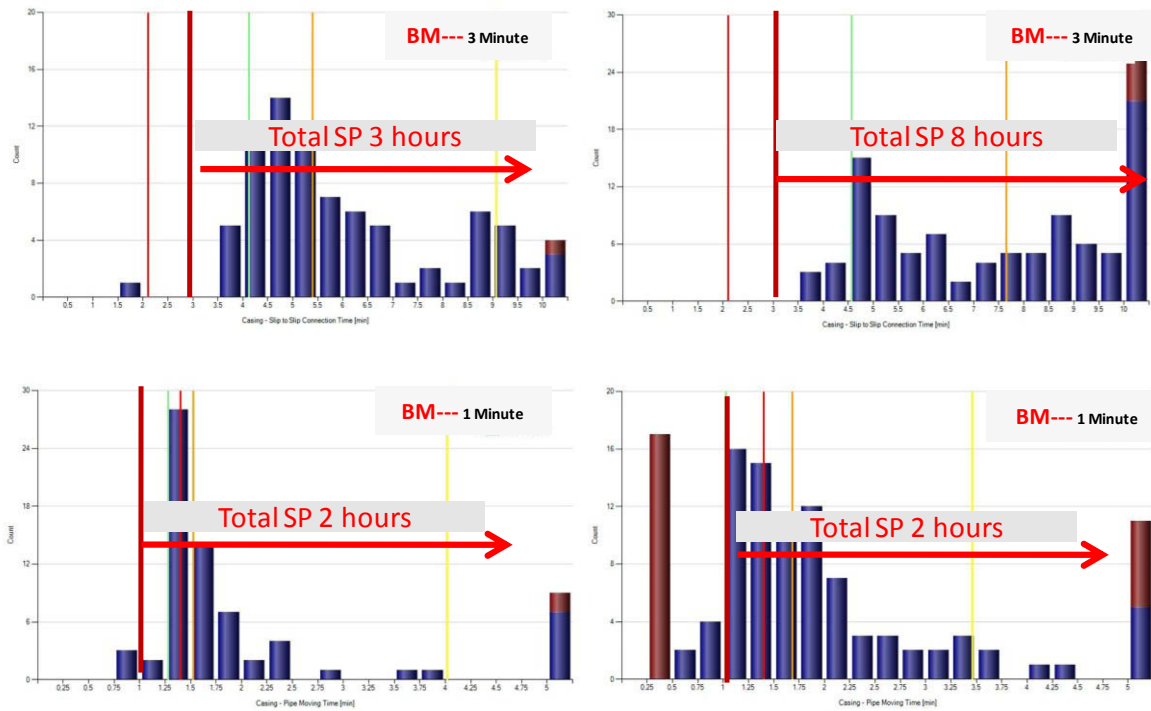

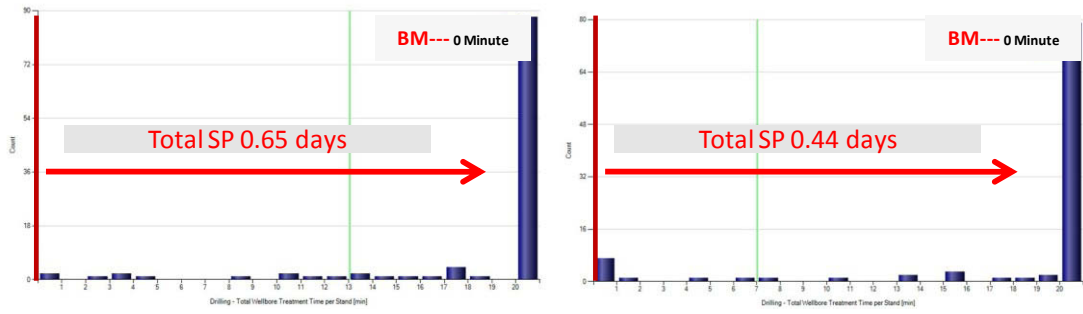Figure 67. Casing Slip to Slip Connection and Pipe Moving Time Histogram for Rig A and B

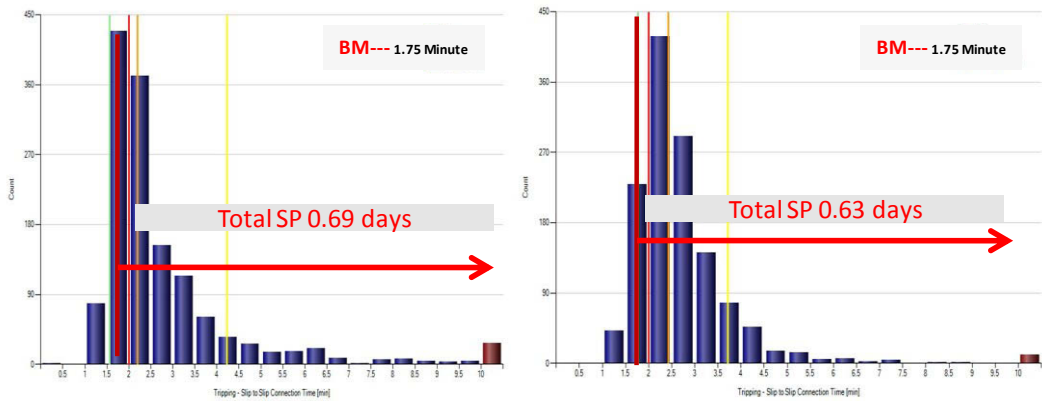Figure 68. Well Bore Treatment While Drilling Histogram for Rig A and B

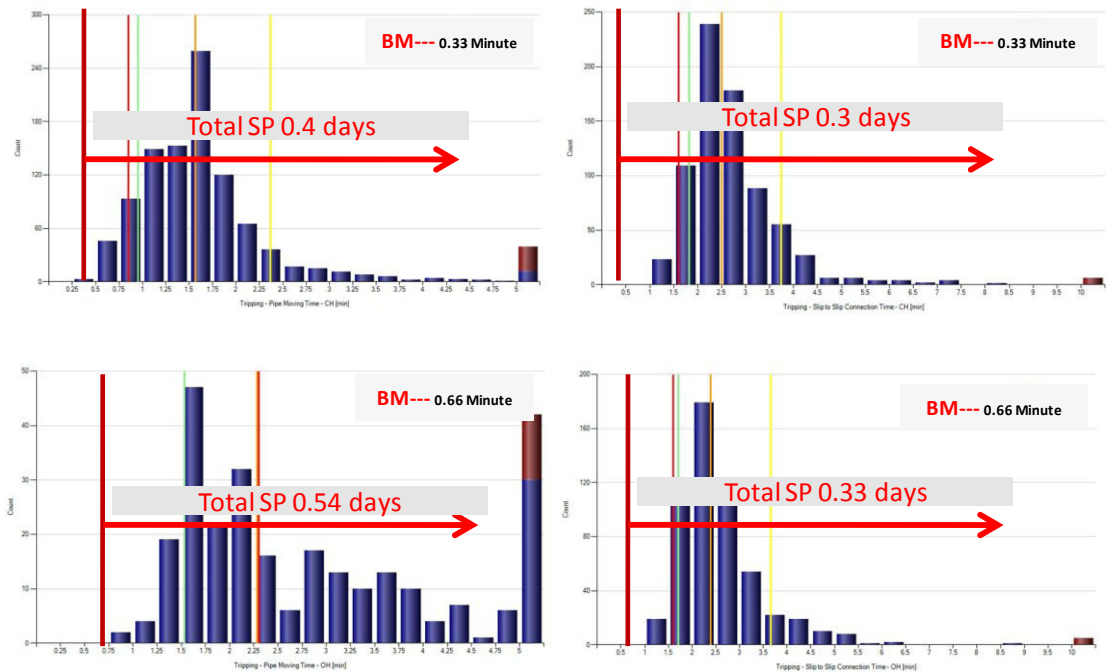Figure 69. Tripping Slip to Slip Connection Time Histogram for Rig A and B

Figure 70. Tripping Pipe Moving CH and OH Time Histogram for Rig A and B
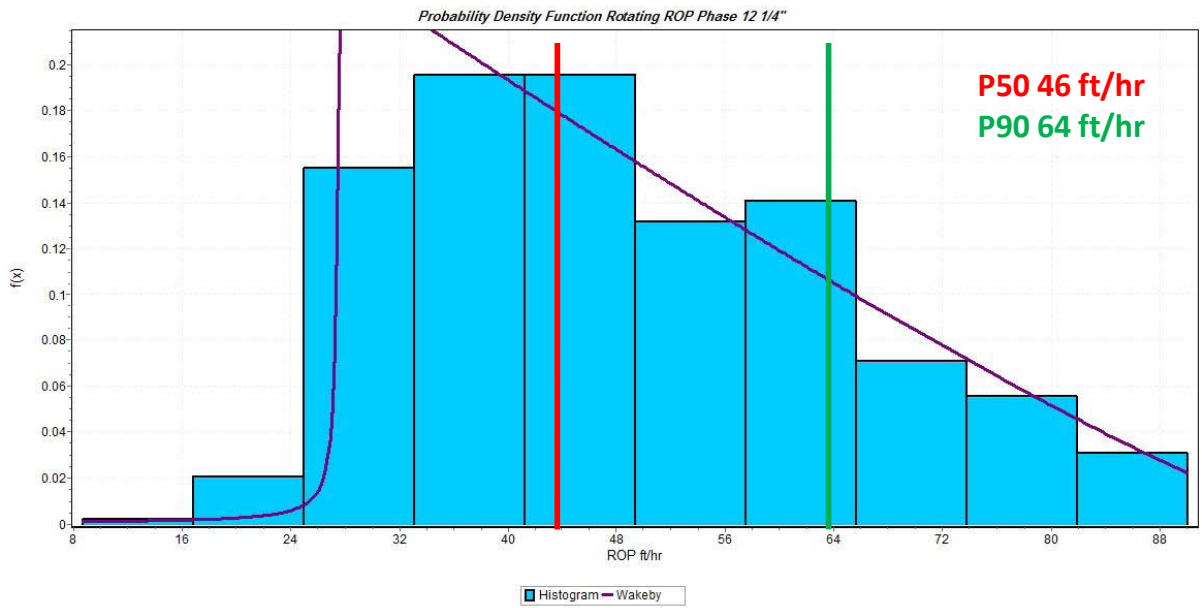
Appendix E

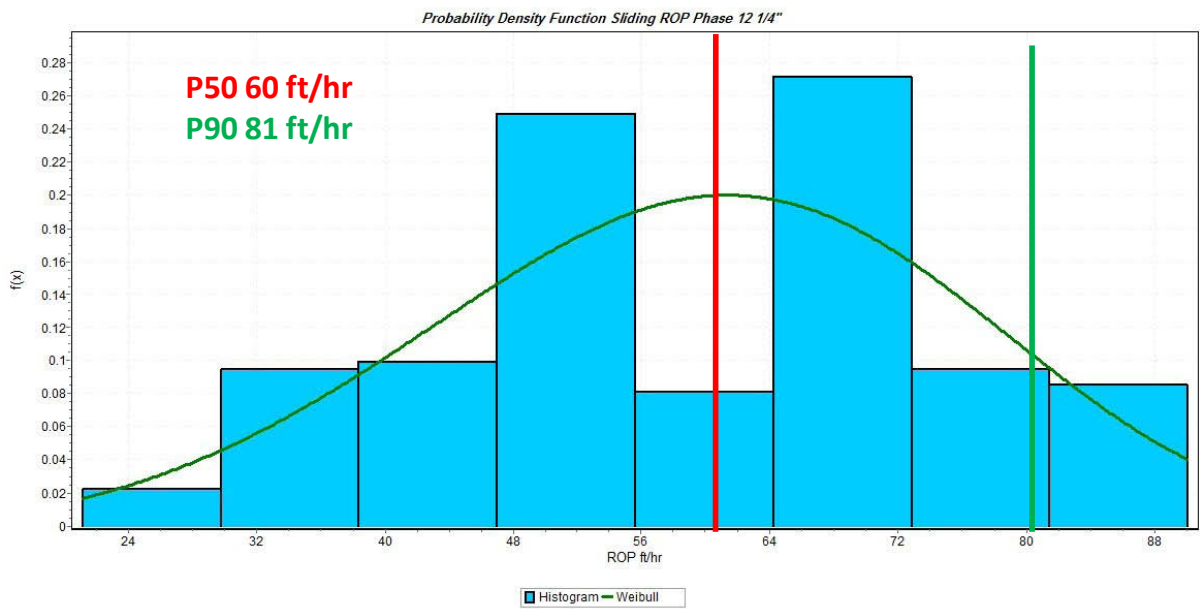Figure 71. Probability Density Function 12 ¼" Phase Rotating ROP Plus P50 and P90

Figure 72. Probability Density Function 12 ¼"" Phase Sliding ROP Plus P50 and P90
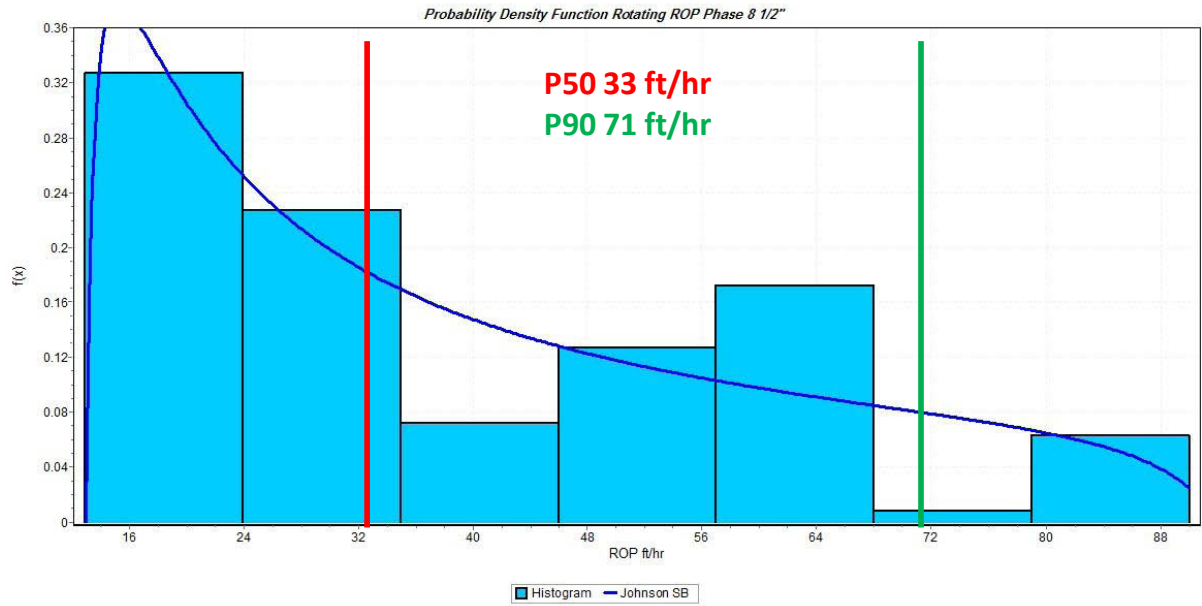
Figure 73. Probability Density Function 8 ½" Phase Rotating ROP Plus P50 and P90
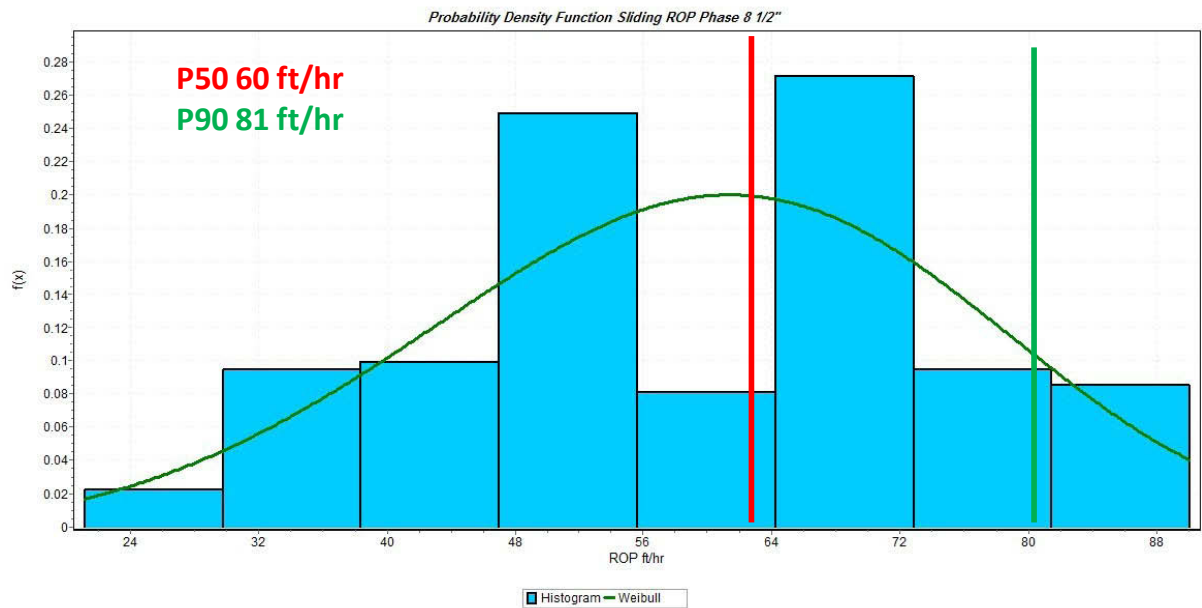

Figure 74. Probability Density Function 8 ½" Phase Sliding ROP Plus P50 and P90