DRILLING TIME OPTIMIZATION USING DIFFERENTIAL EVOLUTION

BY

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عمادة الدراسات العليا
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بسم الله الرحمن الرحيم

Dedicated to my beloved Parents

And

All family members

Whose Prayers and Perseverance led to this accomplishment

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All praises and glory is to **Allah** (subhana wa taala), our God, the most beneficent, the most compassionate, and the most merciful for endowing me with the strength and patience to accomplish this degree.

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LIST OF ABBREVIATIONS

ROP: Rate of Penetration

RPM: Rotary Speed

WOB: Weight on Bit

MW: Mud Weight

BHA: Bottom Hole Assembly

MD: Measured Depth

DDR: Daily Drilling Reports

MLD: Mud Logging Data

CCR: Confined Compressive Rock strength

UCR: Unconfined Compressive Rock Strength

N_{fevs}: Number of Function Evaluations

ABSTRACT

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Drilling of an oil well is a very expensive operation. Consequently, operating and service companies often seek to minimize drilling costs by optimizing the drilling process. The most important factor in cost consideration is the length of time during which a drilling rig is hired. The fact that the rigs are often hired on a day rate means that the longer the drilling time, the higher the drilling cost. Thus drillers often seek to minimize the total time required to drill a well in order to minimize the drilling cost. However, the drilling time is often made of many components, some controllable and others uncontrollable. While the most common factor drillers seek to minimize is the time spent on the actual mechanical drilling of the well, this is not necessarily the most time consuming part of the drilling operations. Minimizing the time spent on the actual drilling is done by seeking optimum parameters that increase the rate of penetration of the bit. Another factor that helps in reducing the total rig time is reducing the frequency at which the bottom hole assembly (BHA) is pulled out of hole to change worn out bits. In this respect, it’s important to consider optimizing drilling parameters to elongate the bit life.

In this study optimization for drilling operations was carried out by finding the optimum parameters values that reduce the drilling time and the total time, taking in the consideration the drilling rate (ROP) and the bit life at the same time. Differential

evolution algorithm was used as the optimization tool. The work involved adequately defining the problems to be solved, formulating the objective of drilling optimization task into mathematical equations and using Differential Evolution to solve the formulated optimization problem.

ملخص الرسالة

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عنوان الرسالة: تحسين زمن الحفر عن طريق استخدام التطور التبايني

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حفر بئر نفط من العمليات المكلفة جدا و بالتالي كل الشركات المشغلة ومتعاقدي الحفر و شركات الخدمات تبحث عن طرق تقليل تكلفة الحفر عن طريق تحسين و تطوير عملية الحفر، العامل الأهم في تكلفة حفر الآبار هو الزمن الذي على أساسه تؤجر أبراج الحفر. أبراج الحفر غالبا تؤجر بمعدل يومي و هذا يعني ان الزمن الأطول المستغرق في عملية الحفر يتتطلب تكلفة أعلى، و من هنا الحفارون يبحثون دائما لتقليل الزمن الكلي المتتطلب لحفر بئر. زمن الحفر عادة يقوم على أساس عدة مكونات، بعضها متحكم به والأخريات غير متحكم بها والعامل الشائع والذي يبحث الحفارون لتقليليه هو الزمن المستغرق في عملية الحفر الميكانيكة للبئر وهذا ليس بالضرورة أن يكون الجزء الأكبر في تبديد زمن عمليات الحفر. تقليل الزمن المستغرق في الحفر يتم عن طريق البحث عن قيم معاملات الحفر المثالية والتي تزيد معد اختراق مثقب الحفر. عامل آخر يساعد في تقليل الزمن الكلي لبرج الحفر هو تقليل عدد المرات التي يسحب فيها عمود الحفر من باطن البئر لتغيير مثقاب الحفر البالي و بهذا الخصوص من المهم اعتبار تحسين معاملات احفر لزيادة عمر مثقاب الحفر.

في هذا البحث تم تحسين عمليات الحفر عن طريق ايجاد قيم معاملات الحفر المثالية والتي تقلل زمن الحفر والزمن الكلي آخذين في عين الاعتبار معدل الحفر و عمر المثقاب في نفس الوقت. خوارزمية التطور التبايني استخدمت كوسيلة تحسين في هذه الدراسة. العمل تضمن على نحو ملائم تعريف المشاكل ليتم حلها، صياغة الغرض من مهمة تحسين الحفر في شكل معادلات رياضية و استخدام تقنية التطور التبايني لحل مشكلة التحسين المصاغة.

CHAPTER 1

INTRODUCTION

1.1 Overview

The increasing cost of drilling an oil well dictates that efficient ways of minimizing the overall cost of drilling operations must be proffered. It is very common to hire a drilling rig on a daily rate. The day rate is often significant running into hundreds thousands of dollars in some cases. Thus, the major determinant of the overall drilling cost is the total time spent drilling the well. The overall time is further divided into two major categories. The first is the productive time, which is the time spent in boring the hole, cementing, logging the well sections and in carrying out other drilling related operations. The second is the non-productive time (NPT), which is the time spent in changing bottom hole assembly and in resolving problems associated with drilling.

Such problems may include stuck pipe in hole, broken strings, lost circulation and hole collapse. In many cases, the NPT is much larger than the productive time, especially if it takes too long to resolve problems encountered during drilling, some others due to failure of drilling equipment or formation can be avoided when drilling operations are carefully planned and efficiently carried out. While some actions that may consume time, such as running out of hole to change worn out bits, cannot be avoided. Therefore, the optimization of drilling operations becomes indispensable if the overall drilling time and consequently cost of drilling a well is to be reduced.

Different methods have been used in the oil industry to optimize drilling operations. A very common approach is learning from past drilling experience in the same or similar field. It is often the case that the first well drilled in a newly discovered field is more expensive than subsequent wells drilled in the same field. This is often due to the lack of good understanding of the geology and drilling hydraulic requirements of the new field. As more wells are drilled, more information about the formations in the field is obtained. Also, previous mistakes are documented and avoided during subsequent drilling operations. Thus, learning curves are used to improve subsequent drilling operations and avoid practices that could lead to potential drilling problems.

In recent years, drilling operations have been enhanced by deploying improved drilling equipment and telemetry systems. The drilling string and bit architecture have been improved significantly to enable drilling in difficult terrains and withstand intense environmental conditions. Such enhancements to downhole equipment have often resulted in reducing the number of times the bottomhole assembly (BHA) is pulled out of hole for replacement.

Improvements in bit efficiency has resulted in improved drilling capacity of the bit and made it possible to drill a longer hole section before the bit becomes dull. Furthermore, recent drilling systems are fitted with downhole recording and telemetry systems that allows real-time acquisition of data and transfer of information to a central control room for onward processing and real-time decision making. This improvement in data acquisition and communications technology has further enhanced drilling operations, reduced risks and consequently reduced drilling cost.

Even though, the variables that have significant effects on the drilling rate (ROP) are not fully understood and are complex to model, several empirical equations have been formulated to relate these variables to the ROP. Commonly optimized drilling parameters are the weight on bit (WOB), the rotary speed of bit (RPM) and the mud hydraulics. Increasing the ROP is the most common optimization objective in the drilling industry. However, more than just increasing the ROP needs to be done to reduce the total rig time. We should pay attention for bit wear rate as well, hence we are looking for the parameters that reduce the total time by considering the ROP and the bit life at the same time.

In this research, differential evolution optimization (DE) technique was used to find ROP values and consequently the drilling parameters values that leads to minimize the drilling time and the total time of drilling operations, the total time include running in hole time, pull out of hole time plus an hour or two for handling collars and bits at the surface. DE is a stochastic search algorithm that has a high possibility of locating the global optimum parameters of an objective function.

The first part of this work involved minimizing the drilling time using the DE algorithm, so the only objective here is the drilling time. Initial a minimum value for the bit wear function (W_f) which will be defined later has been specified, at which the bit should be pulled out and changed by new one and run in hole again to resume the drilling until the end of the section. The second part of this work discussed minimizing the total time using the mentioned optimization algorithm, the total time included tripping and connection time.

Also in this part many cases were studied by changing the minimum value of the wear function Wf and total time for each case was recorded.

The ROP and the bit life have been optimized to reduce the total rig time. In this regard, the bit life is not the length of time the bit drills before it becomes dull but the length of hole section the bit is able to drill in a reasonable time frame before it becomes dull. It is important to note here that drilling very fast (high ROP) is not necessarily equivalent to drilling a longer section of the formation (larger bit life). So it is important to manage the drilling rate and the bit wear rate to achieve the optimum scenario.

1.2 Problem Statement

One of the most common methods to reduce the drilling cost is optimizing the drilling parameters to maximize the ROP which has a direct effect on the total time and cost. But the problem is there are some parameters that increases the ROP such as increasing the WOB and RPM may cause the bit to wear quickly, Cooper et al. [1], thus preventing the bit from drilling a longer section before the BHA is pulled out of hole for bit replacement. Therefore it is essential to note the time wasted by changing the bits several time can erode any gains from increased drilling rate (ROP).

1.3 Objective of the Thesis

The main objective of this study is using Differential Evolution as an optimization technique to minimize the drilling time and the total time required to drill a section. In drilling operations, total time includes the trips time, reaming time, circulating and survey time, and the time required for handling collars and bits at the surface, this will be achieved by finding the optimum parameters values that give the minimum overall time required to drill a specific section and this will be achieved by optimizing the ROP and the bit life, another objective is to show through this optimization technique that maximizing ROP doesn't always mean reducing the total time.

1.4 Research Approach and Methodology

During the stages of the work, relevant data, equations and correlations have been collected from previous work, some of the most useful models that relate the model and drilling parameters such as WOB, rotary speed, flow rate, etc to objectives such as drilling rate and bit dulling rate have reviewed and collated.

Specifically, the work involved the following stages:

Data and Information Gathering: To conduct this study real data from filed in north of Africa has been obtained , drilling data such as rate of penetration, hole cleaning, bit efficiency, drilling parameters values with the depth, mud weight design data, rock strength and rock abrasiveness data.

Data Quality Check and Assurance: After the data has been obtained QC/QA process has been performed in order to increase the reliability of the data.

Rock strength data (ARSL): a rock strength data has been obtained for the same filed.

Model Development: after the model has been specified and all the required data collected, analysis was performed in order to evaluate all the required coefficients according to our field data to make the model suitable for that field.

Model Validation: comparison between the calculated ROP and Actual ROP has been done to ensure the validity of the model for the optimization process and acceptable matching achieved.

Problem Formulation: As mentioned earlier, the aim of this study is minimizing the drilling and the total time required to drill the a section, the total time includes the drilling time, trips time, reaming times, circulating time, survey time, and the time of connecting, disconnecting, handling the pipes at surface and bit change time .

A minimum value for the wear function has been specified, at which the drilling should stop and pull the string out to change the bit and run it in hole again to resume drilling.

Then the single objective problem involved minimizing the drilling and total time required to drill the section and this gives the optimum ROP values and consequently the drilling parameters which recommended for each the bit run.

The objective function for the drilling time for the entire section is given by:

$$Drilling\ Time\ = \sum_{i=1}^{n} \left(\frac{IL}{ROP}\right)_i \quad (1.1)$$

And the total time for the entire section is given by this equation

$$Total\ Time\ = \sum_{i=1}^{n} \left(\frac{IL}{ROP}\right)_i + \sum_{b=1}^{nb-1} (Trips\ time)_b + \sum_{b=1}^{nb-1} (Bit\ Change\ time)_b \quad (1.2)$$

The ROP is the modified warren model.

IL: Interval length (ft)

n: the number of the intervals

nb: the number of bit runs

Cases of maximizing the parameters to increase ROP have been investigated and the total time recorded and compared to the optimum parameters cases.

High ROP means drilling fast but definitely will accelerate the bit wear, hence many bits will be used and this will require additional time for bit change, while using optimum ROP may consume more drilling time for the single bit run but will extend the bit life and enable it to drill longer section, and this means minimizing the numbers of the bit runs and consequently the tripping time required for bit change.

Other cases have been studied by changing the minimum value of the wear function $W_{f.}$

So the ultimate goal is finding the case that minimize the total time, hence the solution of this problem will be recommendation to apply the parameters values of WOB, RPM and flow rate generated from that case.

Identification of the constraints and variables: drilling constraints and design variables that can lead to minimum rig time have been identified while ensuring safe operating conditions.

Solution Algorithm: Deferential Evolution algorithm has been identified to solve the formulated drilling optimization problem.

Coding: The DE algorithm identified or developed to solve the problem has been coded in MATLAB©. The optimization problem also has been coded and the code describing the formulated problem was coupled to appropriate DE code to solve the problem.

Applications: The algorithm has been tested on two drilling sections and many minimum Wf values.

CHAPTER 2

LITERATURE REVIEW

Numerous techniques of drilling optimization have been used in the recent years to minify drilling operation cost. This is accomplished by diminution of the operation time, and as we know time is always money in drilling operations, the concept of time taking for any drilling operation can be represented in terms of drilling rate of penetration, Therefore; estimation of the rate of penetration through drilling models is one of the major parts of the drilling optimization.

In this part we are reviewing some of the drilling models that have been developed in the past, but what is the drilling model?

“A drilling model is usually a mathematical relationship which relates rate of penetration to the parameters affecting it significantly. There is no exact mathematical relation between drilling rate and different drilling variables because not only a large number of uncertain drilling variables influence drilling rate, but also their relationship is nonlinear and complex” Ricardo et al. [2].

“Penetration rate is affected by many parameters such as bit hydraulics, weight on bit, rotary speed, bit type, mud properties, formation characteristics, etc.” Akgun [3].

2.1 Drilling Rate Models

Many efforts have been exerted in ROP modeling since 1960’s, the model published by Galle and Woods [4] is the model for soft-formation bits that has been used most frequently. This model is inadequate as discussed by Randall and Estes [5]. The basic problem with the model is that it cannot be applied in a practical situation without violating the assumptions from which it was developed. In addition, the model does not reflect properly the effect on penetration rate of changing WOB and rotary speed when all other conditions remain constant

Maurer [6] derived a drilling rate formula for roller-cone bits from rock cratering mechanisms. The formula was based on the assumption that perfect hole cleaning was achieved during drilling. The author established a relationship between the ROP, WOB, rotary speed, bit diameter and rock strength.

2.1.1 Bingham Model

Bingham [7] developed model, but Bingham Model is a simple model which is a modification of Maurer Model (an experimental model which is applicable to low value of WOB and N). Also this model neglects the depth of drilling so the answer often has less reliability.

$$R = a\left(\frac{W}{d_b}\right)^b N^c \qquad (2.1)$$

a is the constant of proportionality that includes the effect of rock strength and b is the bit weight exponent .

In 1974 Bourgoyne and Yung [8] proposed using eight functions to model the effect of most of important drilling variables.

2.1.2 Bourgoyne and Young Drilling Rate Model

Bourgoyne and Young [9] suggested that the main parameters which influence rate of penetration are formation strength, bit type, mud type, solid content, compaction, overbalance, bit weight, rotary speed, bit tooth wear and bit hydraulics. They have proposed the following equation to model drilling rate of penetration when using roller cone bits:

$$ROP = f_1 * f_2 * f_3 * f_4 * f_5 * f_6 * f_7 * f_8 \quad (2.2)$$

The term f_1 is defined in the same unit as rate of penetration, for that reason it is called the drillability of the formation of interest.

$$f_1 = e^{2.303a_1} \quad (2.3)$$

The functions f_2 and f_3 model the effect of formation compaction as follows

$$f_2 = e^{2.303a_2(10000-D)} \quad (2.4)$$

$$f_3 = e^{2.303a_3D^{0.69}(g_P-9)} \quad (2.5)$$

The effect of overbalance on rate of penetration is represented by the function f_4 as indicated in below equation

$$f_4 = e^{2.303a_4D\,(g_P-\rho_c)} \quad (2.6)$$

The functions f_5 and f_6 model the effect of bit weight, rotary speed and bit diameter as shown in the below equations respectively

$$f_5 = \left[\frac{\frac{w}{d_b}-\left(\frac{w}{d_b}\right)_t}{4-\left(\frac{w}{d_b}\right)_t}\right]^{a_5} \quad (2.7)$$

$$f_6 = \left(\frac{N}{60}\right)^{a_6} \quad (2.8)$$

The function f_7 implies the effect of bit tooth wear on penetration rate as follows:

$$f_7 = e^{-a_7 h} \quad (2.9)$$

The function f_8 models the effect of bit hydraulics on penetration rate as shown in Equation. Jet impact force was chosen as the hydraulic parameter of interest, with a normalized value of 1.0 for f_8 at 1000 lbf.

$$f_8 = \left(\frac{F_j}{1000}\right)^{a_8} \quad (2.10)$$

2.1.3 Warren's Drilling Rate Model

A model of the drilling process for tri-cone bits called perfect-cleaning model was derived by Warren [10] in 1987 and later modified by Hareland and Hoberock [11]. The basic idea is that under steady-state drilling conditions, the rate of cutting removal from the bit is equal to the rate at which new chips are formed. This implies that the ROP is controlled by the cutting-generation process, the cutting removal process, or a combination of the two processes.

The perfect-cleaning model which is shown in the following equation is reviewed as a starting point for development of an imperfect-cleaning model.

Perfect-cleaning model

$$ROP = \left(\frac{aS^2 d_b^3}{N\,W^2} + \frac{c}{Nd_b}\right)^{-1} \quad (2.11)$$

Unfortunately, ROP in most field cases is significantly inhibited by the rate of cuttings removal from under the bit. Thus Equation 2.11 is not effective for predicting field ROP without modification to account for imperfect cleaning. Therefore, it is necessary to modify the ROP model for imperfect cleaning conditions that represent the real drilling situation.

Sutko and Meyers [12] studied the effect of the impact pressure around the bit area, they stated that the measured impact force should be independent of the nozzle size and a fixed value of the impact force obtained from the flowing equation:

$$F_j = 0.000516\,\rho\,q\,v_n \quad (2.12)$$

The increased fluid entrainment of a jet that flows into a reverse flowing fluid is a function of the ratio of the jet velocity to the return fluid velocity. The area available for fluid return flow from under a roller-cone bit is equal to 15% of the total bit area. If Av is the ratio of the jet velocity to the fluid return velocity, so Av (for three jets) is given by:

$$A_v = \frac{v_n}{v_f} = \frac{0.15\, d_b^2}{3 d_n^2} \tag{2.13}$$

Then the impact force modified for nozzle size effects and the influence of the return flow is given by Equation

$$F_{jm} = (1 - A_v^{-0.122}) F_j \tag{2.14}$$

Dimensional analysis was used to isolate a group of variables consisting of the modified impact force and the mud properties to incorporate into Equation 2.11 to account for the cutting removal. This results in an imperfect-cleaning model:

$$ROP = \left(\frac{a S^2 d_b^3}{N\, W^2} + \frac{b}{N d_b} + \frac{c d_b \gamma_f\, \mu}{F_{jm}} \right)^{-1} \tag{2.15}$$

2.1.4 Modified Warren's Model

Neither Winters et al. [13] nor Warren [10] addressed Chip hold down effects on penetration rate modeling, but it is known that this effect is important. It is an estimation of the resultant forces on a chip when it is generate by the bit. To establish the best relationship for chip hold down, data from laboratory full scale drilling tests was used in which bottom-hole pressure varied and other conditions remained constant. A reasonable fit to this data for different lithologies is given by:

$$f_c(P_e) = c_c + a_c(P_e - 120)^{b_c} \tag{2.16}$$

where Pe is the differential pressure. $f_c(P_e)$ is defined as the “chip hold down function” and a_c, b_c and c_c are lithology dependent constants. Units on a_c, b_c and c_c chosen such that $f_c(P_e)$ is dimensionless.

So now the ROP model is modified to include chip hold down effect and becomes

$$ROP = f_c(P_e)\left(\frac{aS^2 d_b^3}{N\,W^2} + \frac{b}{Nd_b} + \frac{cd_b\gamma_f\,\mu}{F_{jm}}\right)^{-1} \tag{2.17}$$

Hareland and Hoberock [11] modified this ROP model for the effect of bit wear on rate of penetration by introducing a wear function W_f into the model:

$$ROP = W_f[\,f_c(P_e)\left(\frac{aS^2 d_b^3}{N\,W^2} + \frac{b}{Nd_b} + \frac{cd_b\gamma_f\,\mu}{F_{jm}}\right)^{-1}] \tag{2.18}$$

$$W_f = 1 - \frac{\Delta BG}{8} \tag{2.19}$$

Where ΔBG is the change in bit tooth wear. It can be calculated based on the WOB, ROP, relative rock abrasiveness and confined rock strength.

$$\Delta\text{BG} = W_c \sum_{i=1}^{n} WOB_{\ i\ .} RPM_i . Ar_{abri} . S_i \tag{2.20}$$

Rock compressive strength is a function pressure and lithology:

$$S = S_o(1 + a_s P_e^{b_s}) \tag{2.21}$$

where, S and So are the confined rock strength and unconfined rock strength, respectively. The coefficients a_s and b_s depend on the formation permeability.

This model will be used in this study because it is the most representable one for the actual situation.

2.1.4.1 Model Development

In order to determine the general equation for Warren's model for specific formation or area, its constant coefficients must be computed. Coefficients a_c, b_c and c_c are the lithology dependent constants. a_s and b_s are coefficients which depend on formation permeability. These coefficients are presented in Table 2.1. Coefficients a, b and c which are called bit coefficients can be determined by simply plotting the dimensionless group ND/R versus S^2 D^4/ W^2. Using the least square data fitting method a straight line is fitted to the data which results in a slope of a and an interception of b. as far as first two constants are known, third constant can be calculated.

Bit wear coefficient, Wc which is a coefficient for bit grade change shown in ΔBG equation, Equation 2.20. This coefficient is a unique number for each bit run and can be determined according to the dull condition of the corresponding bit, Rahimzadeh et al. [14].

Table 2.1: Chip hold –down and rock strength permeability constants

Formation	Permeable	Impermeable
P_e	$P_h - P_p$	P_h
a_c	0.00497	0.0141
b_c	0.757	0.47
c_c	0.103	0.569
a_s	0.0133	0.00432
b_s	0.577	0.782

2.1.4.2 Apparent Rock Strength Log (ARSL)

It is critical to obtain the rock strength parameters along the wellbore. Different sources can be used to develop rock strength information. Such strength information is important when assessing the stability of the wellbore, selecting the mud weight and designing casing programs. To obtain the rock strength along the wellbore, petrophysical logs, rock mechanical laboratory tests and rock mechanical tests on small cutting samples can be used. Rock mechanical laboratory testing on preserved core samples is the most accurate method for calculating rock strength. However, well preserved core samples for conducting laboratory measurements are rare and the testing procedure is rigorous. On the other hand, the logs are often available only in the reservoir sections of the wells which will limit the availability of continuous rock strength along the wellbore. One source of data that is often overlooked in calculating rock strength is drilling data. The advantage of using drilling data to calculate rock strength is that they are available for the entire well not only the reservoir zones. Also, this rock strength is directly connected to the predictability of ROP, Rastegar et al. [15].

Using of simulators to generate ARSL logs was discussed by Nygaard et al. [16], they mentioned that during the past eight years a drilling optimization simulator has been applied to different fields in the North Sea with good results. The simulator is based on penetration rate models and uses offset drilling data through inverted drilling models to obtain an apparent rock strength log (ARSL).

The Drilling Optimization Simulator (DROPS) is developed to reduce the cost of future wells based on apparent rock strength log (ARSL), created from the drilling data collected on a previous well drilled in the same area. The ARSL is created using ROP (Rate of Penetration) inverted to calculate rock compressive strength. The simulator has the capability of simulating any combination of operating conditions, bit design, pull depths, hydraulics, WOB (Weight on Bit) and RPM.

2.2 Studies on ROP models

Rahimzadeh et al. [14] analyzed the two sophisticated models, Bourgoyne and Young Model and Modified Warren's Model , they performed a study on SK filed located on the Qatar –Fars Arch , one of the major structural elements of the Central Persian Gulf Area. They collected stratigraphic column and geological description of each formation for a typical two wells in this field. They've chosen 12 ¼ hole section because most of the time and money consumed here.

The constant coefficients of Bourgoyne and Young model have been obtained for two wells by using genetic algorithm. The resulted coefficients have been used to evaluate rate of penetration at each data point.

Since the drilling models constant coefficients might not be the same for different formations or bit runs, drilling data have been categorized so that the models can be developed for specified formations and bit runs, individually.

According to what has been mentioned previously about development of Warren's model, the bit constants and bit wear coefficients of Warren's model for the two bits have been evaluated.

They figured out that the accuracy of Bourgoyne and Young model depends on the accuracy of the mathematical method used for determination of the model's constant coefficients. In comparison, Warren's model accuracy is affected significantly by how accurate the data has been recorded. The row rock strength data is of poor quality, since it is obtained from sonic log data which is influenced by many parameters and contains a large amount of noises.

Also they stated Warren's model estimation results fall in a shorter ROP intervals compared to the Bourgoyne and Young model. Hence, one might expect Warren's model to better estimate ROP in formations which their ROP values usually fall in a short interval, while Bourgoyne and Young model is capable of estimation of ROP where it varies over a wide interval of ROP values.

The paper concluded that application of Warren's model is recommended when a high quality and reliable rock strength data is available and usage of Bourgoyne and Young model is suggested when effect of drilling parameters is more important. However, both models practically should be applied in compliance with previous experiences in the same field.

Bataee et al. [17] stated that there are many methods to reduce the drilling cost of future wells, one of these methods is optimizing of drilling parameters to obtain the maximum rate of penetration (ROP) in each bit run, the main parameters affect ROP are hole cleaning, rotation speed (N), weight on bit (WOB) tooth wear, formation hardness and differential pressure. The authors emphasized that each part of well has different recommended parameters from the other parts. To optimize the drilling parameters, it is required that an appropriate ROP model to be selected until acceptable results are obtained.

In literature, there are various applicable models to predict the ROP such as Bourgoyne and Young model, Bingham model and modified Warren model. It is desired to calculate and predict the proper model of ROP for roller-cone and PDC bits in each well by using the mentioned models and then verify the validity of each model by comparing with field data. Analyzing the drilling parameters by computer optimization yields recommended range of parameters for each bit. The applications of this study are predicting the proper penetration rate, optimizing the drilling parameters, estimating the drilling time of well and eventually reducing the drilling cost for future wells.

2.3 Applications of ROP (drilling) optimization algorithms

Baataee and Mohesni [18] demonstrated that Artificial Neural Networks (ANNs) is a helpful tool in recognizing complex connection between many parameters affecting the rate of penetration .Genetic algorithm (GA), as a class of optimizing methods for complex functions, is applied to help ROP optimization and its related drilling parameters. In this study and modeling process the proper parameters are selected based on the desired ROP to be achieved ,in model used here ,bit diameter , depth ,WOB,RPM and mud weight have been fed as the inputs for ANN while ROP is set to be the output .
The study showed the ability of ANN analysis whether no equation to find the actual amounts of parameters which maximize penetration rate. Great range for N and WOB is used and observed that best one was neither the maximum nor the minimum value. An appropriate ROP was selected based on the previous ROP to be achieved by using the modeled function and applying the corresponding drilling bit parameters.

Artificial neural network (ANN) drilling parameter optimization system was developed by Gidh et al. [19] to provide rig-site personnel real-time information to ensure maximum run length from all bits and downhole tools at the highest possible ROP. Benefits of the new system include extended tool life, fewer trips and the ability to manage the bits dull condition.

The objective was to replace the human factor of applying operating parameters such as WOB and RPM with the intelligent ANN learned experience. Using the ANN software system, operating parameters can be selected based on the documented physical rock characteristics (offset log data) of formations being penetrated and then fine-tuned for the bits specific cutting structure and wear rate. By following the real-time ANN recommendations, changes can be implemented to increase overall ROP while maximizing bit life by managing the dull condition.

The authors mentioned that the real-time artificial neural network (ANN) drilling parameter optimization system may recommend reducing operating parameters, which can slow ROP which normally increases drilling costs, but preserving the bit's cutting structure can enable the operator to complete the run without tripping for a new bit thereby reducing overall cost/ft.

In the case of the new real-time drilling parameter optimization program, the sophisticated ANN system actually "learns" how the bit drills and dulls in similar lithologies and downhole tendencies of similar bottom hole assemblies .The ANN then uses this "learned experience" to offer the best combination of surface parameters including flow rate, weight on bit (WOB) and RPM to efficiently achieve the operator's requirements, the study showed positive results

Khamis [20] have done a study on parameters optimization, the main objective of this study is to develop a technique to optimize the drilling parameters in real time to achieve the maximum rate of penetration based on the drilling specific energy (DSE).

PSO was used successfully to minimize the DSE in order to determine the maximum ROP corresponding to the optimum drilling parameters.

CHAPTER 3

DATA ACQUISITION AND PREPARATION

3.1 Introduction

To conduct this study real data from fields in North Africa were collected from two types of sources: (1) Daily drilling report (DDR) which is the daily report written by the company men on the rig site, summarize the daily drilling operations events with the time on codified activities .

This type of report has a description for BHA, bit data, mud records, hydraulics etc., and this type considered as the standard source of the drilling information, Zausa et al [21].

Another and less used source of this information is: (2) Mud log data (MLD) or the master log, this log is generated by mud logging unit using the sensors on the rig. The master log contains a detailed description of the formations and lithology along the well depth. And also some of them show continuous records such as logs for the drilling parameters (ROP, WOB, MW, SPP, Flow rate) and brief description for some events in the drilling operations.

Zausa et al. [21] studied drilling time analysis through the combination of the operations reporting (DDR) and sensors data (MLD) and made a comparison between these two types of sources, as shown in Table 3.1.

They've stated also that each type of the mentioned sources has some weaknesses; the main weaknesses of the DDR are concentrated on the subjectivity from human bias in operations interpretation, and the rather long time frame of operations descriptions (every 30 minutes). MLD weaknesses are related to the difficulty to analyze a huge number of data records, because there are no direct correspondences with operational activities and other events.

Table 3.1 DDR and MLD comparison

	PROS	CONS	CONCLUSION - negative, + positive
Daily Drilling Report (DDR)	○ Precisely descriptive ○ Codified ○ Standard ○ Ready to use	○ Long time frame (mini 30 mn) ○ Subjective ○ Interpretation error ○ Discontinuity quality	Reliability + Sampling - Usability + +
Mud Log Data (MLD)	○ Short time frame (less than 5 seconds) ○ Automatic ○ Continuous quality	○ Limited activities detectable (Bit on Bottom, Circulation, Tripping, Reaming, On Slip) ○ Data need retreatment & calculation	Reliability + Sampling + + Usability - -

So the data used in this study were extracted and combined from the two sources in attempt to increase the overall data accuracy.

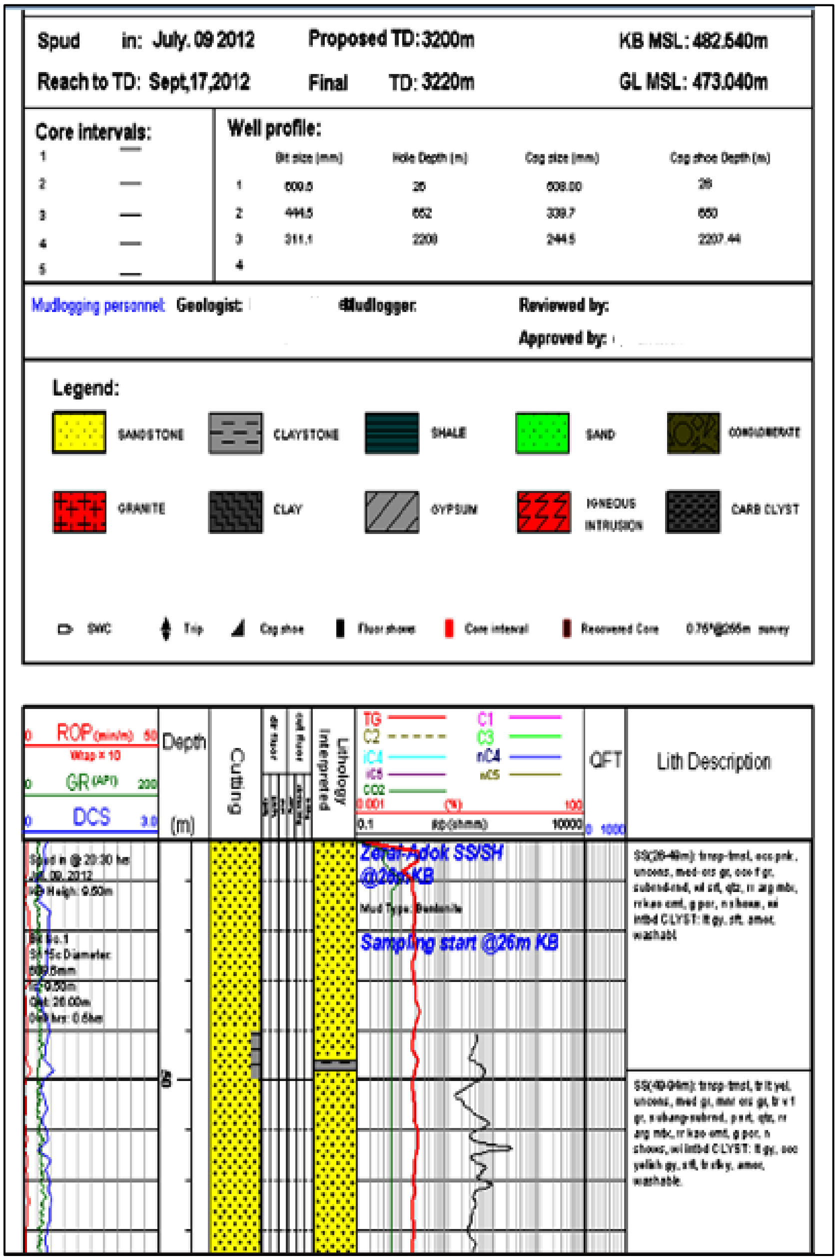

Figure 3.1 MLD

Table 3.2 DDR

Well name	Field	Block	Report Date	Report No.	Report Sending Time	From spud in			
		6	8/23/2012	46/12	8/24/2012	45	day	3.50	HRs
Well Class	Well Type	AFE NO.	AFE Cost	Authorize Depth(m)	Moving Date	Spud in time	TD Date	Released Date	
Appraisal	Vertical	121403		3200.00		20:30 9.07.2012			
Contractor	Rig	Type of Rig	Drilling Capacity	RKB	Hook load	Rig Class	Target Formation	Formation	
02/2010-6190	Asawer D-2	1200HP	3700m	9.2m	225t	Land			
Last Casing size	Casing Depth (m)	BOP Test	Casing Test	Next Casing Size	Hole Size	Ground Elevation (m)	KB Elevation		
9 5/8"	2208.00	12 Mpa	12 Mpa	5 1/2"	8 1/2"	468.004	478.004		
Total Dep	Last night Dep	Footage(m)	Drilling Time	ROP(m/h)	Operation at 6:00 o'clock for report sent day	Next Operation			
2718.00	2698.00	20.00	7.00	2.86	Cont. drilling 8-1/2" hole to 2734 m.	Wiper trip			

BHA			Bit Data		Mud Record				Hydraulic		
Element	OD/ID	Length	Run in No.	1	Silicate -II		Mud material		Bit No.		9
Bit	8½"	0.24	Bit No.	9	Dep-Sam(m)	2718	KPAM		S.P. P.(Mpa)		14.5
Bit-sub	0.91	0.91	Manufacture	kingdream	Temp.(℃)	64	XY-27		Flow rate(l/s)		34.75
17x6½" DC	2 13/16"	159.59	Type	HT-J437GC	Density	1.19	Caustic soda		AV.DC.(m/s)8"		
6 1/2" D.Jar	2.8"	9.46	Size(mm)	8-1/2"	Viscosity	51	CAT-NW		AV.DC.(m/s)7"		
3x6½" DC	2 13/16"	28.23	IADC	437	600	63	JT-888		AV.DC.(m/s)6 1/2"		2.29
9x5" HWDP		83.43	Serial no.	08650	300	42	Soda ash		AV.DP.(m/s)5"		1.45
			Jets	[illegible]	3	3.0	FT-1		AV.CAS.(m/s)		
			Depth in(m)	2698	PV	21	SPNH		E.A.(cm²)		
5" DPs		2433.64	Depth out(m)	INC.	YP	10.5	KCL	2.0	Nozzle Velocity(m/s)		73.00
			Footage(m)	19.38	GEL	3 5	Liquid casing		Drop nozzle(Mpa)		3.40
			Hours	7.00	Filtrate(ml)	4.7	XCD	2 sacks	H.HP.(Kw)		163.00
			ROP	2.77	mud cake(mm)	0.5	Silicate	10 bbls			
			WOB(kN)	10-140	KCL %	6.10	Polycol-1		PUMP		
Kelly down		2.50	RPM(r/min)	70-85	Silicate %	9.00	NH_4-HPAN		Items	NO.1	NO.2
Total		2718.00	E.D.(cm)		Solids	7.50%	RH-3		Make	Lanzhi	Lanzhi

Force of drilling string		Low Pump Rate Test		Bentonite(g/l)	20.00	Barite	1 bags	Type	3NB-1300C	3NB-1300C
static	230000lbs	Stroke	Pressure	sand content	0.30%	HFX-101		liner	165	172
up	238000 lbs	MP#1 17/25 SPM	220/290 Psi	PH	13	PAC-RL		L of S	305mm	305mm
down	220000 lbs	MP#2 17/25 SPM	250/320 Psi	Chloride	28925	PAC-LV		SPM	50	50

Solid Control	Shale Shake		Desander								Centrifuge			
	No.1	No.2	time	UF	OF	m³/h	time	UF	OF	m³/h	time	UF	OF	m³/h

Deviation	Depth	2688	angle	2.25°	Depth	2629		angle	1.5°	Depth	2449	angle	1.5°

Time	Drill	Trip	Circulation	Reaming	Lubricate rig	Survey	Logging	Csg &cmt	repair	Slip&cut line	WOC
	8.75	9.25	0.75	2.25		1.25				1.75	

Distribution	Rig up&down	Preparation	Test CSG & BOP	N/U BOP	Others	Total
						24.00

Personnel		Crew		wire line logging	Mud logging	Security	Mud engineer	Total
	2	37	1		6	4	2	52

From	To	Hrs.	Code	Operation content	Type	Rate(US$/H)	Accum.(US$)
00:00	07:00	7	6	Cont. RIH W/ 8½" Bit F/113m to2208m	OP	572.92	4010.44
7:00	8:45	1.75	9	Slip & Cut Drilling line	SB	572.92	1002.61
08:45	11:00	2.25	6	Cont. RIH W/ 8½" Bit F/2208m to2657m (Touch down : 10-15t @ 2650m -2661m)	OP	572.92	1289.07
11:00	13:15	2.25	3	Ream & circulate F/2657m to 2698 m	OP	572.92	1289.07
13:15	14:00	0.75	5	Circulate	OP	572.92	429.69
14:00	15:15	1.25	10	Resurvey 2.25°@2688m.	OP	572.92	716.15
15:15	24:00	8.75	2	Drill 8½" main hole F/2698m to 2718m	OP	572.92	5013.05

** Formation : xxxx: SS 25 %, CL 75 %

3.2 Well Structure

Well A has been used in this study, it has a total depth of 3200 m, the structure of the well is shown in Figure 3.2.

The study focused on the intermediate (12 ¼) and main (8 ½) holes because most of the time and cost are consumed on these two sections.

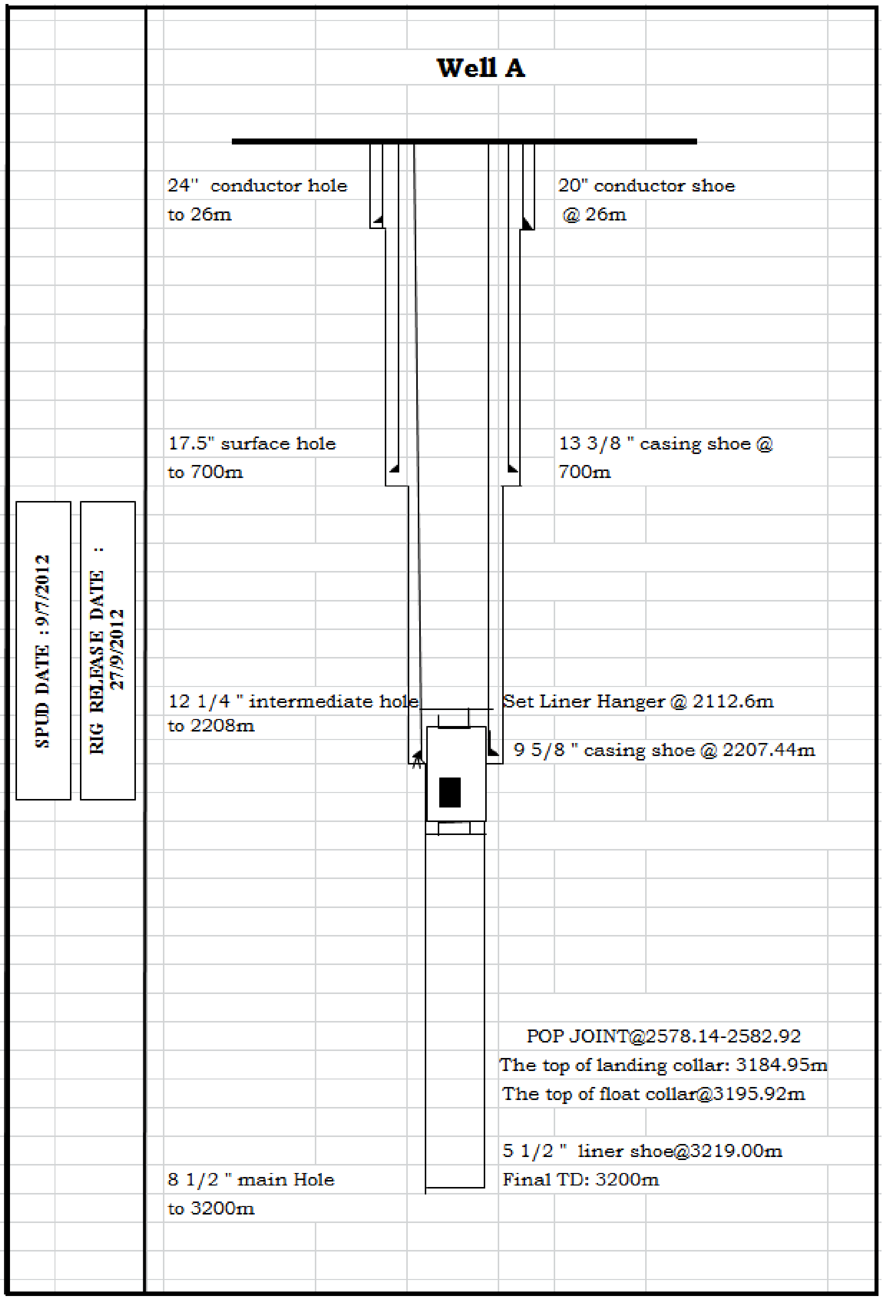

Figure 3.2 Well A profile

3.3 ROP Data (12.25″ section)

Since the ROP data is the most important part of the drilling data, QC/QA process has been performed by obtaining the values from reviewing the DDR and the master log for each 50 meter then, taking the average of the two values (DDR and MLD) for each data point in order to increase the accuracy of ROB data.

So the Figure 3.3 shows the ROP from the DDR and MLD for the intermediate section,

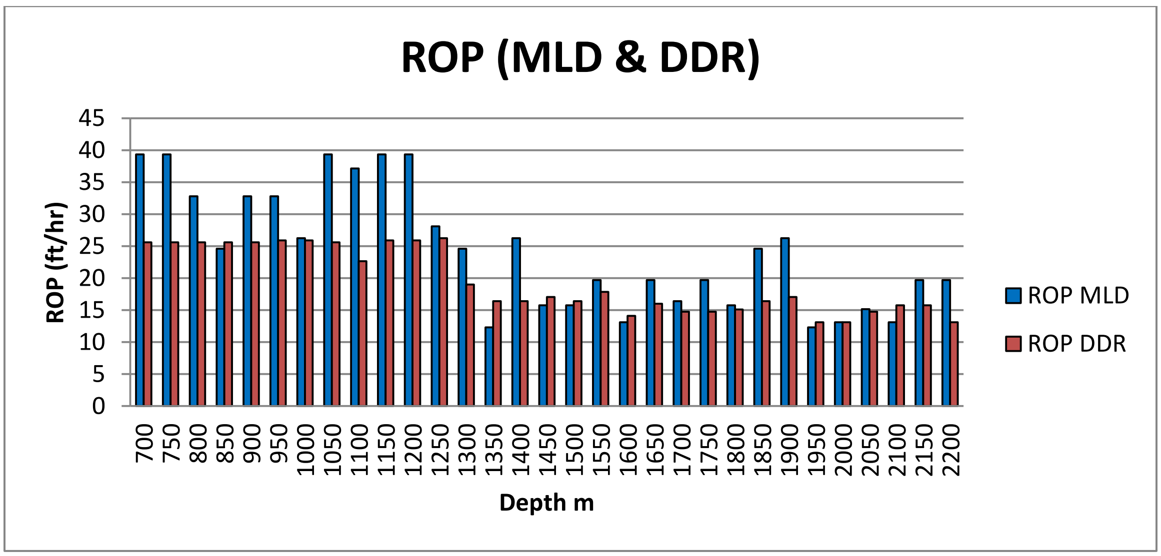

Figure 3.3 Comparison between ROP from MLD and DDR (12.25 section)

The merged ROP which is considered as the actual ROP values for the intermediate section is shown in Figure 3.4.

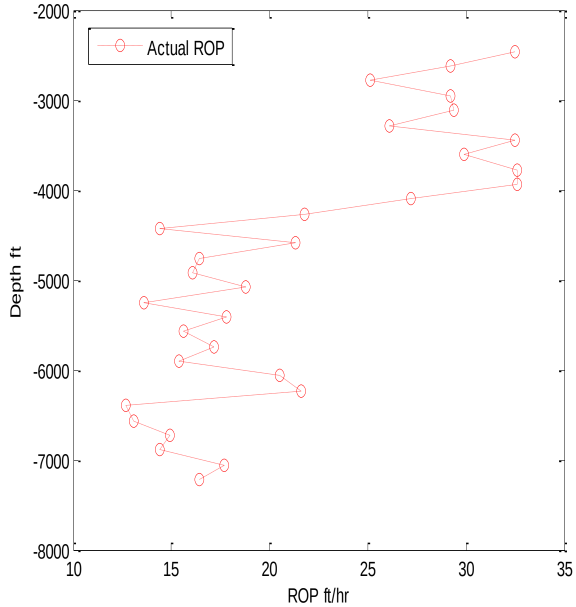

Figure 3.4 Actual ROP well A (12.25″ section)

3.4 ROP Data (8.5″ section)

Figure 3.5 shows the ROP values of the DDR and MLD for the main section.

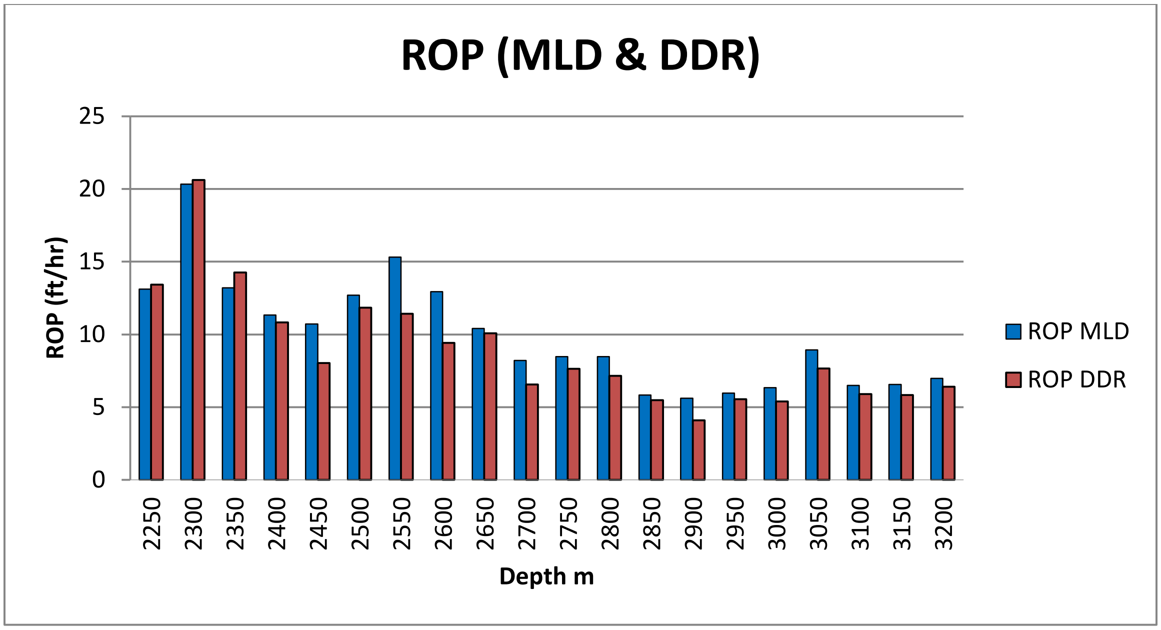

Figure 3.5 Comparison between ROP from MLD and DDR (8.5″ section)

The averaged ROP obtained by taking the average of the MLD and DDR values for the main section is shown in Figure 3.6.

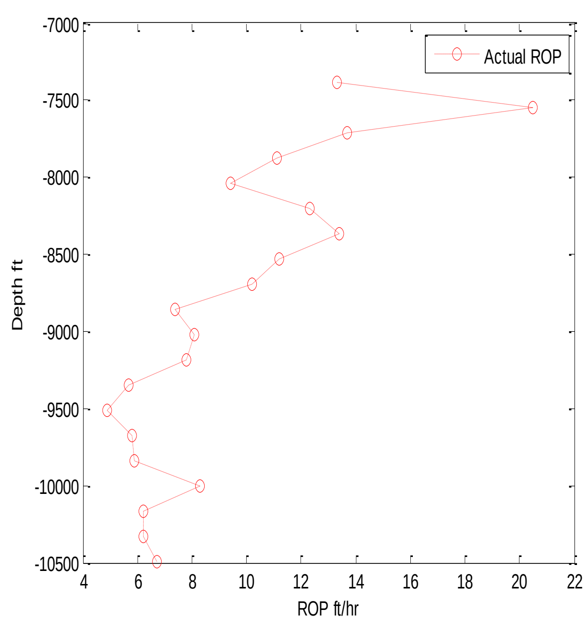

Figure 3.6 Actual ROP well A (8.5 section)

3.5 Drilling Parameters

One of the essential parts of the data required to conduct this study is the drilling parameters along the depth, Table 3.3 shows the summary or the average parameters values obtained from DDR and MLD that have been applied in this well for each bit run.

The bit manufacturers normally recommend parameters according to the bit specifications to be applied in the field, in attempt to achieve the maximum efficiency of these bits, but sometimes due to the rig specification or capacity, these parameters values can't be applied. However an example of recommended operating parameters sheet provided by the bit manufacturer shown in Table 3.4.

Table 3.3 Drilling parameters

Bit Number	Bit Size (in)	Interval		Drilling Parameters					
						Flow rate			
		From (m)	To(m)	WOB kN	RPM r/min	Liner mm	SPM s/min	flow rate GPM	SPP MPa
1	24	9.30	26.00	10-30	50-60	170	100	538.91	7.2
2	17.5	26.00	700.00	100-120	80	170	150	825.80	9.24
3	12.25	700.00	1305.79	50-100	70-90	170	140	766.04	12.39
4	12.25	1305.79	1638.70	30-100	70-90	172	135	766.04	12.39
5	12.25	1638.70	1991.00	50-140	70-90	172	130	673.64	13.5
6	12.25	1991.00	2208.00	50-120	70-80	172	130	729.11	14.7
7	8.5	2208.00	2460.72	50-120	70-80	172/165	130	550.80	14.5
8	8.5	2460.72	2698.00	50-140	70-85	172/165	100	550.80	13.5
9	8.5	2698.00	2866.00	120-150	70-85	172/165	100	550.80	14.5
10	8.5	2866.00	2994.28	150-170	60-85	172/165	100	550.80	14.5
11	8.5	2994.28	3200.00	150-170	60-85	171/165	100	528.29	14.3

Table 3.4 Recommended parameters sheet

Recommended operational parameters of Kingdream bits							
Item	Bit size	Series and type	Recommended operational parameters				
			Normal bit weight (KN/mm)	Rotary speed (rpm)	Total revolutions	Recommended make-up torque for bit	Reg. API shank (in)
17	12-1/4"	MD115GLM	0.25---0.70	300~60	20~45	37.9---43.3	6-5/8"
		MD115GLMC	0.25---0.70	300~60			
		MD117GLM	0.30---0.90	300~60			
		MD117GLMC	0.30---0.90	300~60			
		MD517GLM	0.35---1.05	300~60	20~80		
		MD517GLMC	0.35---1.05	300~60			
		MD537GLM	0.50---1.05	300~60			
		MD537GLMC	0.50---1.05	300~60			
		MD547GLMY	0.50---1.05	300~60			
		MD547GLMYC	0.50---1.05	300~60			
18	12 1/4"	SMD417C	0.35---0.90	400~60	30~90	38--43.4	6-5/8"
		SMD427C	0.35---0.90	400~60			
		SMD427XC	0.35---0.90	400~60			
		SMD437C	0.35---0.95	400~60			
		SMD437XC	0.35---0.95	400~60			
		SMD447C	0.35---1.00	400~60			
		SMD447XC	0.35---1.00	400~60			
		SMD517	0.35---1.05	400~60			
		SMD517C	0.35---1.05	400~60			
		SMD517XC	0.35---1.05	400~60			
		HA SERIES					
		HA116	0.35---0.90	150---80			
		HA116C					
		HA117					
		HA117C					
		HA127	0.35---1.00	150---70			

3.6 Bit records

The length of the intermediate section (12 ¼ hole) is about 1500 m (700m-2200m), the drilling of this section required a total of 4 trycone bits. The main hole (8 ½ hole) is about 1000 m and 5 trycone bits were used in that section.

Data for the drilling bits used in this well is shown in Table 3.5.

Table 3.5 Bits Data

Bit Number	Bit Size in	Bit Type	Remarks	Manufacture	Serial Number	Jet Diameter (1/32″)				Interval		Footage m
						1#	2#	3#	4#	From m	To m	
1	24	IADC114	ST Tricone	Kingdream		22	22	22	15	9.30	26.00	16.70
2	17.5	S114C		Chendu		18	18	18	18	26.00	700.00	674.00
3	12.25	MD117GLMC	ST Tricone	Kingdream		18	18	18	16	700.00	1305.79	605.79
4	12.25	HJ437GC	TCI Tricone	Kingdream		20	20	20	14	1305.79	1638.70	332.91
5	12.25	HA427GC	TCI Tricone	Kingdream	088	20	20	20	16	1638.70	1991.00	352.70
6	12.25	HA427GC	TCI Tricone	Chendu	033	20	20	20	20	1991.00	2208.00	217.00
7	8.5	HJ437GC	TCI Tricone	kingdream	08657	16	16	16	16	2208.00	2460.72	252.72
8	8.5	HJ437GC	TCI Tricone	kingdream	08647	18	18	16	14	2460.72	2698.00	237.28
9	8.5	HJ437GC	TCI Tricone	kingdream	08650	16	16	16	14	2698.00	2866.00	168.00
10	8.5	HA527GC	TCI Tricone	kingdream	017341	16	16	16	14	2866.00	2994.28	128.28
11	8.5	HA527GC	TCI Tricone	kingdream	31602	16	16	16	14	2994.28	3200.00	205.72

The data included International Association of The Drilling Contractor classification in the bit type column and also the wear evaluation for some bits in Table 3.6

Table 3.6 Wear evaluation

Bit Number	Bit Size in	Wear Condition							
		I	O	D	L	B	G	O	R
1	24	1	1	BU	A	1	1	NO	TD
2	17.5	2	2	WT	A	I	I	NO	TD
3	12.25	2	4	WT	A	E	O 4/16”	No	PR
4	12.25	2	2	No	A	E	O 1/16”	No	HRs
5	12.25								
6	12.25								
7	8.5								
8	8.5								
9	8.5								
10	8.5	5	5	BT	A	5	1/16	NO	HR
11	8.5	3	3	NO	A	5	1/16	NO	HR

3.7 Total Time

Since the main objective of this research is reducing the drilling time and the total time required to drill predetermined section, the time spent in the actual case should be mentioned to compare the optimization results with the actual data, however, the time spent in each bit run consists of: drilling time which is the time consumed in the drilling operations while the bit rotating and generating cuttings from the bottom, tripping time, reaming time, circulating and survey time.

Below brief definition for some terminologies mentioned above:

Tripping: there are two types of tripping: 1) round trip: which is the physical act of pulling the drilling string out of the well bore and then running it back in, this happen by physically breaking out or disconnecting (when pulling out) the joints and reconnecting the joints (when running in). The most common reason for tripping pipe is to replace the worn drill bit.

2) Wiper trip: is pulling the drilling string to specific point like the casing show and running it again to the bottom, Wiper trips, or dummy trips, are performed to clean the hole during long-hole sections, thus ensuring there are no tight spots, sloughing shale, etc. that may result in tight hole and stuck pipe problems if left unchecked.

Reaming: is performed to open an under-gauge hole to its original full-gauge size. It may be performed to prevent an under-gauge hole from pinching a new bit. A reamer is the tool used to smooth the wall of a well, enlarge the hole to full-gauge size, help stabilize the bit, straighten the wellbore if kinks or doglegs are encountered, most reamers used today have roller cutters in alignment with the axis of the reamer body, which provides a rolling action as the reamer is rotated, Hawker et al. [22].

Circulating: is the process of pumping drilling fluid out of the mud pits, down the drill string, up the annulus and back to the mud pits, and is a continual process while drilling.

Circulating, while not drilling, normally performed to clean the hole of drill cuttings, to condition the drilling mud ensuring it retains optimum properties, or to remove excessive gas from the mud.

Survey: is a single-shot survey recording that provides a single record of the drift angle, or inclination, and (compass) direction of the hole. The single-shot survey instrument is run, on wireline, down through the drill pipe during a temporary halt to drilling operations. A photograph is taken of a compass reading, the drift direction and the number of degrees the hole is off vertical at the current depth. The tool is pulled back to surface and the picture retrieved.

Using this information and allowing for declination (i.e., the difference between magnetic and true North), the amount of drill string rotation required to position the face of the deflection tool in the desired direction can be determined. The information from successive surveys makes it possible to determine well trajectory, deviation and doglegs, Hawker et al. [22].

Table 4.5 shows the sum of each category for the two sections under the study in Well A. from the extensive analysis of the DDRs for this well we found that the wiper trips, reaming, circulating and survey operations are conducted regularly before the round trips in order to avoid some problems that may happen during the pulling and running the BHA to change the bit, because more time consumed when the problems of overpull, stuck pipe, etc., occurred during solving these problems.

So the actual time spent for each category is shown in Table 3.7.

Table 3.7 Time data

Bit Number	Bit Size in	Interval		Drill Time hours		
				Total	Including	
		From m	To m		Drill Actual	Trips and Reaming
1	24	9.30	26.00	4.6	4.1	0.5
2	17.5	26.00	700.00	74.50	60	14.5
3	12.25	700.00	1305.79	88	70	18
4	12.25	1305.79	1638.70	95	72	23
5	12.25	1638.70	1991.00	73	46	27
6	12.25	1991.00	2208.00	96	67	29
7	8.5	2208.00	2460.72	96.6	64.6	32
8	8.5	2460.72	2698.00	113.5	78.5	35
9	8.5	2698.00	2866.00	107.3	70.3	37
10	8.5	2866.00	2994.28	130	90.23	40
11	8.5	2994.28	3200.00	124.2	97.2	27

From the time analysis of the DDRs for Well A, it was found that the average estimation of the trips for each bit run is about 5 hrs/1000 ft, and accordingly this estimation has been included in the objective function of the total time in addition to 2 hours required to change the bit at the surface.

3.8 Drilling Mud Properties

The drilling fluid used in Well A was 100% water base mud which is the common drilling fluid type used in this field. The fluid system consisted of bentonite and other additives from depth 26 m up to 115 m then the fluid system changed to KCL polymer, the use of KCL polymer in this section provides shale stabilization, the inhibitive properties of the system are provided by the addition of KCL, the potassium ions which contribute to cuttings and borehole stability through cationic exchange will provide a more stable wellbore. This system was used to drill to depth 2830 m, then silicate fluid system has been used in last part as an inhibitive mud formulated with a soluble silicate for maximum shale inhibition. Table 3.8 shows the typical properties of the mud used during the drilling of well A.

Table 3.8 Mud data

Bit Number	Bit Size in	Interval		Mud Property				
		From m	To m	Density g/cm^3	Density PPG	Viscosity s	Sand Content %	Filtration ml
1	24	9.30	26.00	1.03	8.58	50		
2	17.5	26.00	700.00	1.06	8.83	44	0.50	5.30
3	12.25	700.00	1305.79	1.10	9.16	47	0.50	4.50
4	12.25	1305.79	1638.70	1.1	9.16	47	0.50	4.50
5	12.25	1638.70	1991.00	1.166	9.71	47	0.5	4.3
6	12.25	1991.00	2208.00	1.19	9.91	49	0.3	4.2
7	8.5	2208.00	2460.72	1.17	9.75	48	0.3	4.8
8	8.5	2460.72	2698.00	1.19	9.91	50	0.3	4.8
9	8.5	2698.00	2866.00	1.2	10.00	53	0.3	4.8
10	8.5	2866.00	2994.28	1.2	10.00	53	0.3	4.5
11	8.5	2994.28	3200.00	1.2	10.00	52	0.3	4.5

3.9 ARSL

As discussed in the literature review awareness of the rock strength data is very important. It helps to control drilling problems such as pipe sticking, tight hole, collapse, pack off and sand production, and it is important factor in controlling the ROP.

Apparent rock strength log or the confined compressive strength (CCS) is given by equation

$$S = S_o(1 + a_s\, P_e^{b_s})$$

Where, S_o is the unconfined compressive strength (UCS), hence the apparent rock strength log or the CCS is obtained from the UCS, the UCS data for this field has been obtained in two forms, one as a map, shows the average rock strength estimation for the formation AG and the other as logs for few wells.

Figure 3.7 is a map shows the top of AG formation.

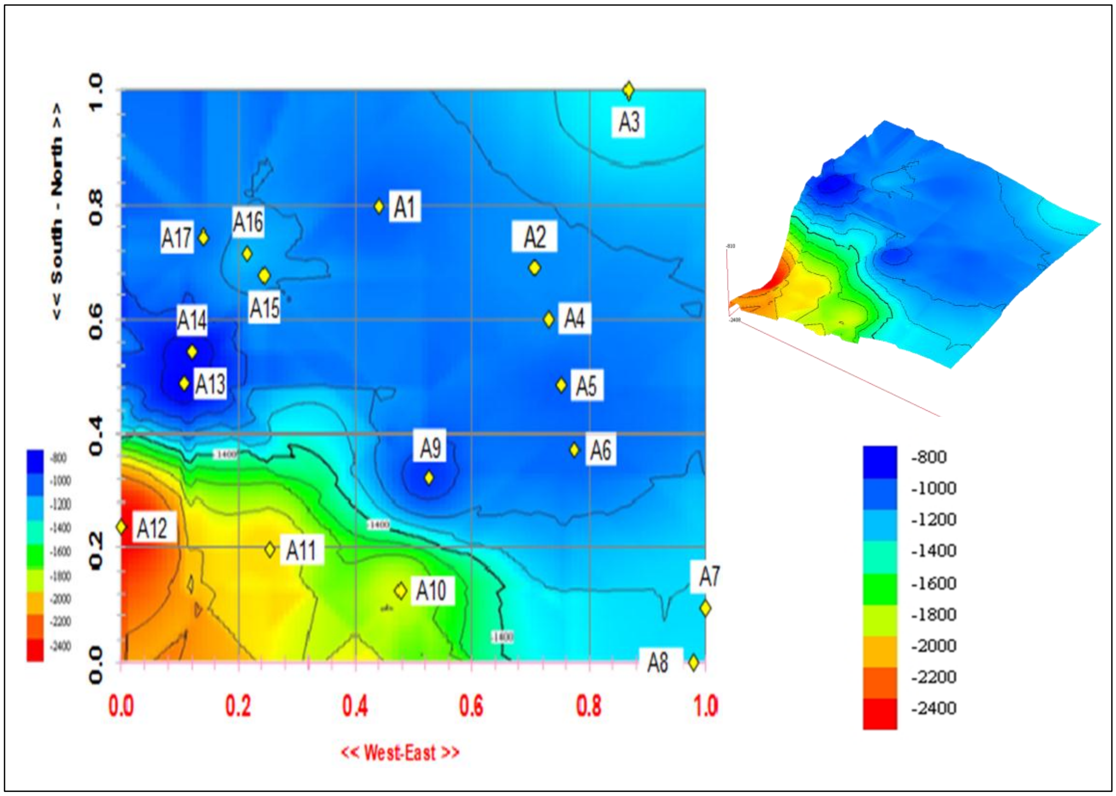

Figure 3.7 Top AG vs well location

Since our study focused on Well A1, the top of the AG formation in that well is at the depth of 800 m. The total depth of this formation is at 3200 m, Figure 3.8.

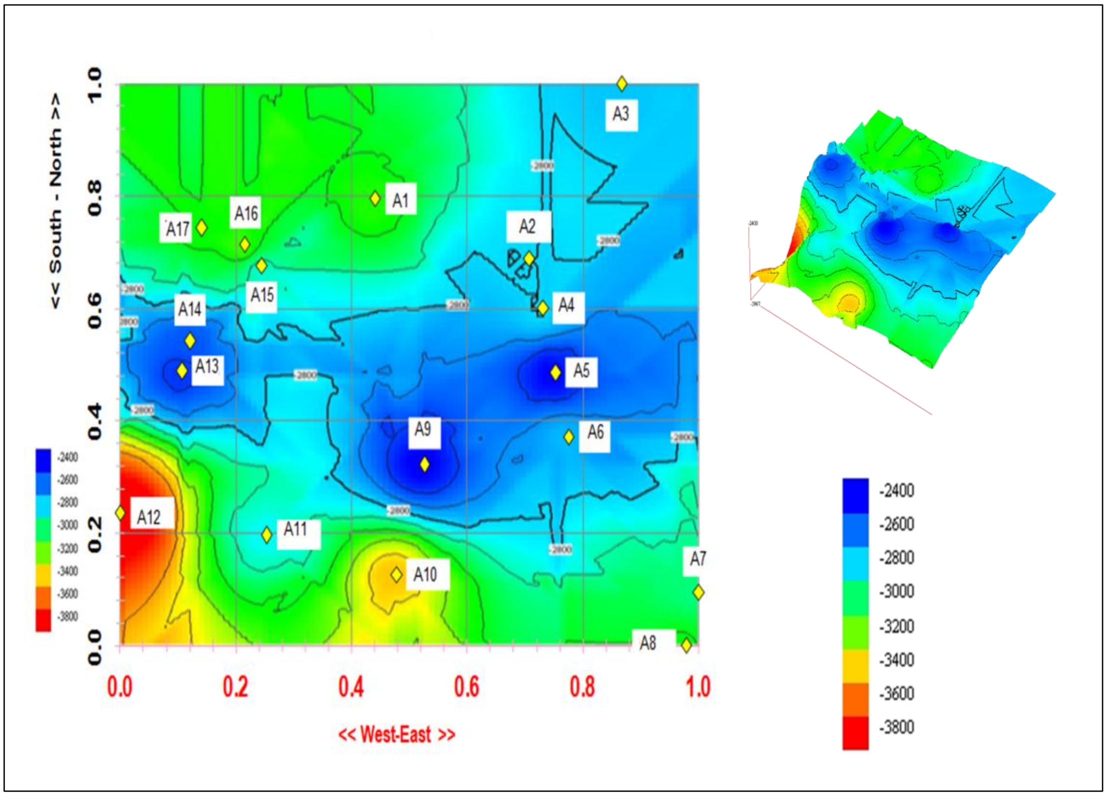

Figure 3.8 TD AG vs well location

The UCS data for this field in the AG formation is shown in Figure 3.9, and as its clear the range of UCS for this field is from 8000 psi to 18000 psi, Well A1 has an average UCS values in the range of 13000 psi to 15000 psi, and generally in the field the places that exhibit high rock strength, have low ROP values as shown in figure 3.10.

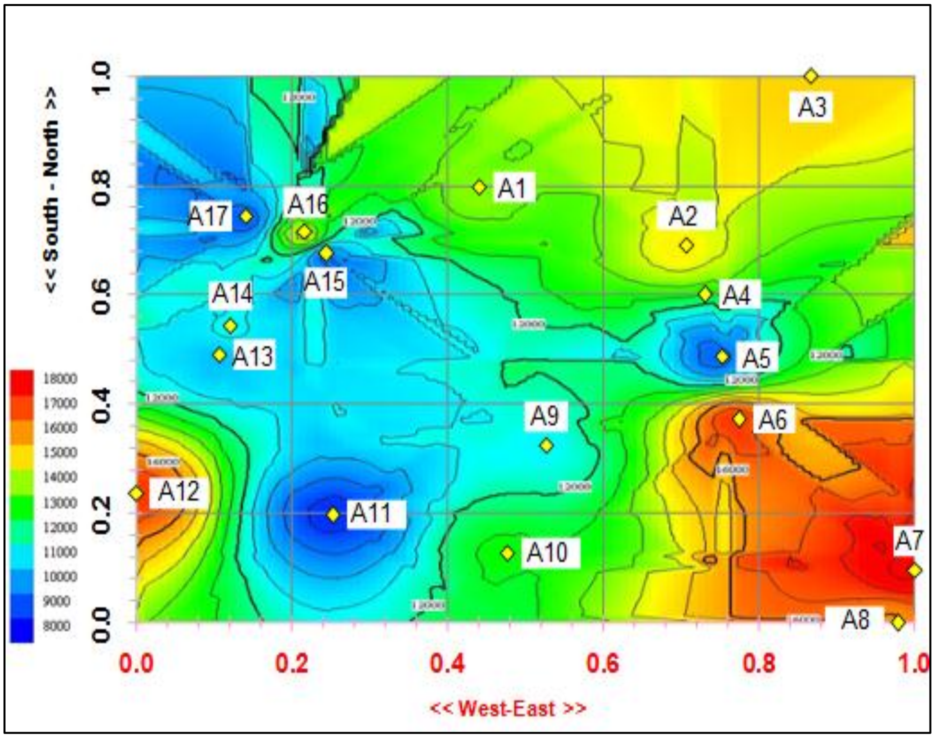

Figure 3.9 UCS AG vs well location

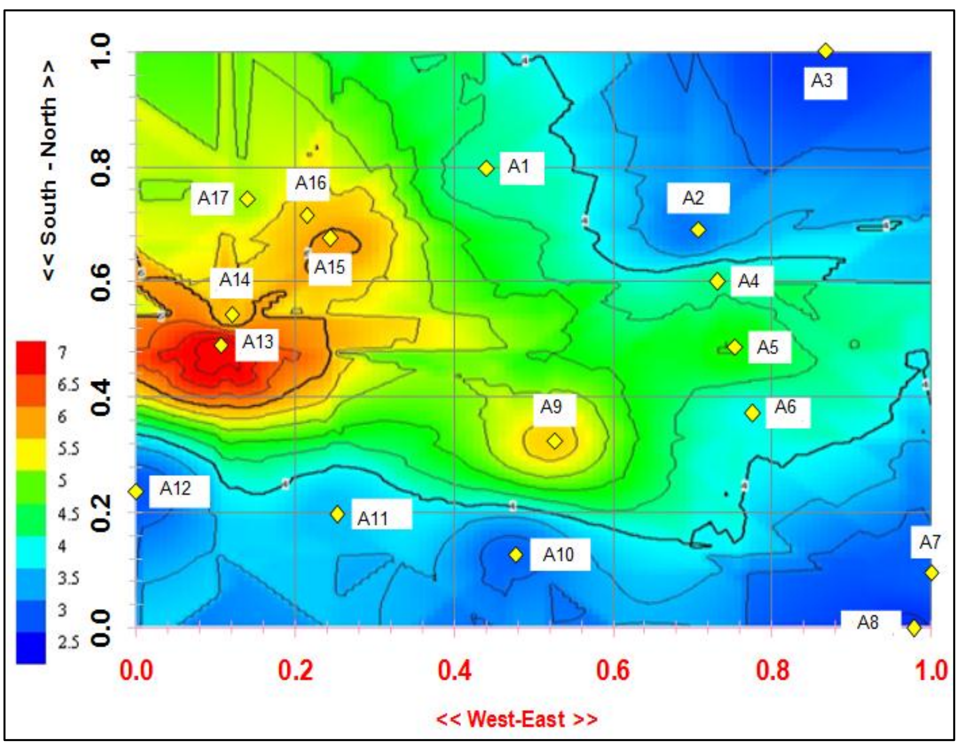

Figure 3.10 ROP AG vs well location

CHAPTER 4

PRE-MODELING ANALYSIS

This chapter discusses the development of the model that was used in this study, and how we found the coefficients from the field data.

Warren’s model has been explained in details in the literature review, and it’s has been mentioned that in order to generate the ROP values for specific formation or interval we should find the bit coefficients a, b and c by the plotting of $\frac{ND}{RF_{(P_e)}}$ versus $\frac{S^2D^4}{W^2}$ for each bit run. Lithology dependent coefficients and formation coefficients presented in the Table 2.1.

Also one of the important coefficients that must be evaluated is Wc which is the bit grade change coefficient. It is a unique number for each bit.

4.1 Intermediate section (12.25″ hole)

4.1.1 Bit Coefficients

The first bit used in 12.25″ section is milled tooth trycone bit. To estimate the constants corresponding to this bit, $\frac{ND}{RF_{(P_e)}}$ vs $\frac{S^2D^4}{W^2}$ should be plotted at the first 100 m, the slope and the intercept of the best line fitted to the data gives values for a and b respectively, the third coefficient c can be assumed to be zero because it’s value usually small and negligible compared to the other two constants. However, the value of this constant can be calculated from the constants a and b and also other parameters including the operating conditions, rock strength and chip hold down function through this equation:

$$c = \frac{F_{jm} * W_f * f_c(P_e)}{d_b \gamma_f \mu * ROP} \left[1 - \left(\frac{ROP}{W_f \; f_c(P_e)} \left(\frac{a S^2 d_b^3}{N \, W^2} + \frac{b}{N d_b} \right) \right) \right] \tag{4.1}$$

Since it is recommended using the first 100 m for the bit run and plotting the parameters for each 2 m data point we used the data from master log of this well. In order to find the required coefficients for the first bit run, we plot in Figure 4.1.

As it's clear in the figure the best trend line fitted to the data is Y=0.002x+ 24.698 which gives us the values of the two coefficients a and b, so a = 0.002 and b = 24.698, the third bit coefficient c was obtained by equation 4.1 for the all data points, and it's average which is 0.00109 was used in the analysis.

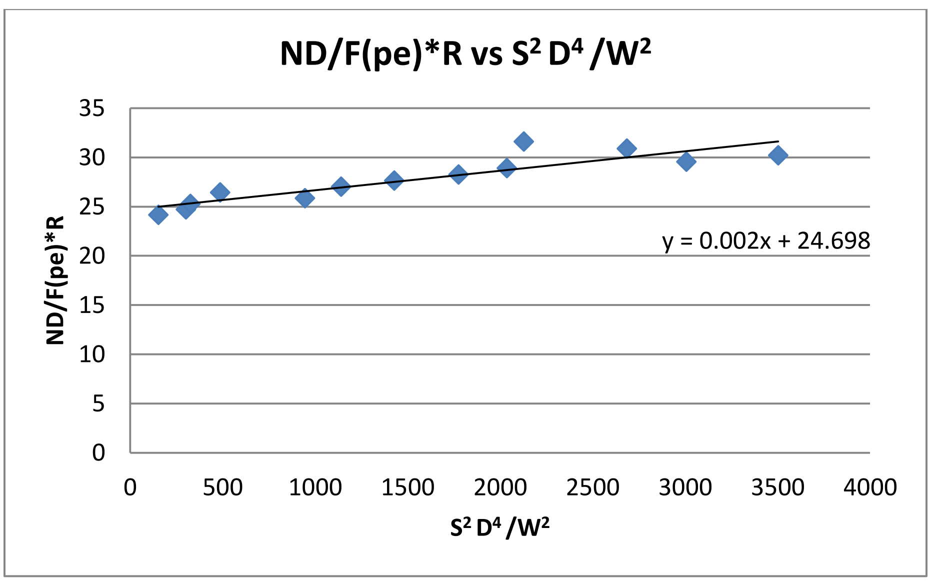

Figure 4.1 Determination of bit constants in 12.25″ section

4.1.2 Bit Wear Coefficient

In order to estimate the bit wear coefficient, we should study the bit dull grading for the bits used in the section, we are more interested in the cutting structure category.

By referring to the bit wear data that was presented on Table 3.4, we can see that the first bit run has given Grade 2 for the inner rows , grade 4 for the outer rows , Grade WT: worn teeth/cutters for the dull characteristics, and grade A: all areas/rows for the location.

For the bearing and seals the bit graded with E: seals effective, and for the gauge condition, the grade is O 4/16". So we can give overall grade for this bit after it is pulled out to the surface considering only the cutting structure is 3 out of 8.

Since we are able now to set Wf values of the bit at the beginning of the bit run which is 1 for the new bit ($\Delta BG = 0$) and at the end of the run = 0.625 ($\Delta BG = 3$), we can find coefficient Wc by the iteration in Equation 2.20 form the start until the end of the run and this gives also wear distribution and the Wf function through the bit run.

So after performing the iteration we find the value of Wc of the firs bit to be 7.e-11.

4.1.3 ROP (Model & Actual) -12.25″ Section

After all the required coefficients (bit & wear) have been obtained, the coefficients were used to evaluate the ROP at each data point by substituting the constant coefficients into the models. Then ROP values are plotted along the depth with actual ROP values for the intermediate section (12.25″ hole) as shown in Figure 5.2.

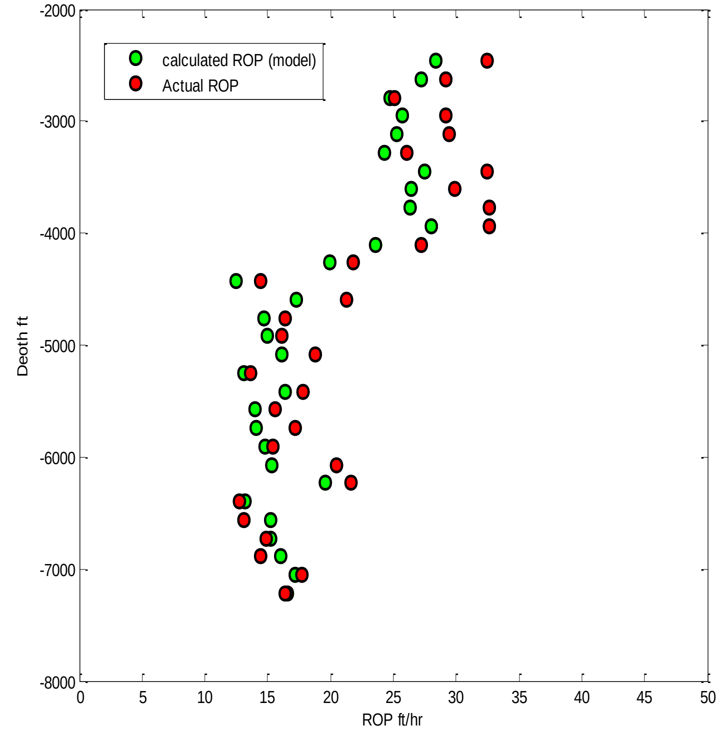

Figure 4.2 Comparison of estimated ROP and actual ROP (12.25 ″ section)

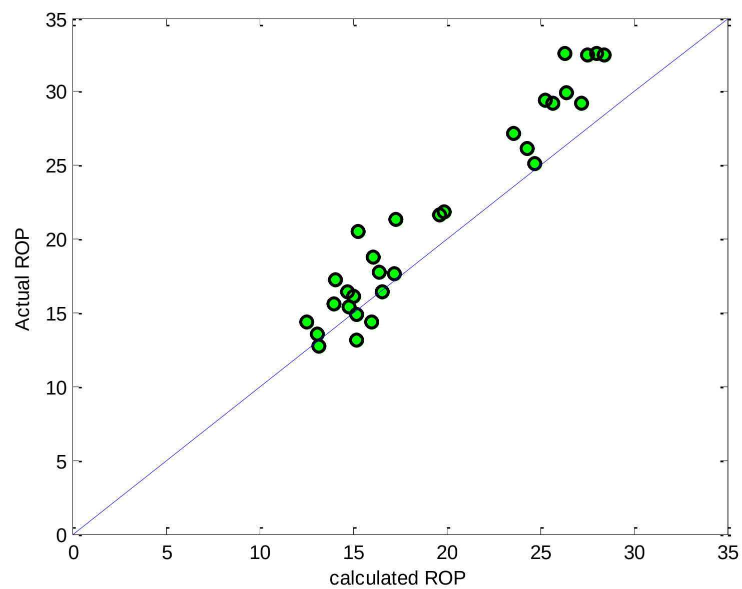

Figure 4.3 ROP actual vs ROP model (12.25″section)

Another plot of predicted ROP from warren model versus actual ROP is shown in figure 4.3.

According to Figure 4.2 we can notice that Warren's model values fall in shorter intervals (15-35 ft/ hr) and this is in compliance with what Rahimzadeh et al. [14] observed in his study. Hence Warren's model is recommended to be used in this field with low ROP values and specifically in the intermediate section where hard rocks and are shale encountered.

So after achieving this acceptable matching of ROP model and actual we can say the model is validated to be used in the optimization algorithm in order to optimize the parameters and predict the ROP and Wf.

4.2 Main Section (8.5″ Hole)

4.2.1 Bit Coefficients

The first bit used in this section is TCI trycone bit, we follow the same approach used in the intermediate section to find the bit coefficients by plotting $\frac{ND}{RF_{(P_e)}}$ vs $\frac{S^2D^4}{W^2}$ in the first 100 m, the slope and the intercept of the best line fitted to the data gives a and b values respectively, the third coefficient can be assumed to be zero because it's very small, or back calculated after getting a and b using the other estimated parameters.

Below the figure shows the plotting of $\frac{ND}{RF_{(P_e)}}$ vs $\frac{S^2D^4}{W^2}$.

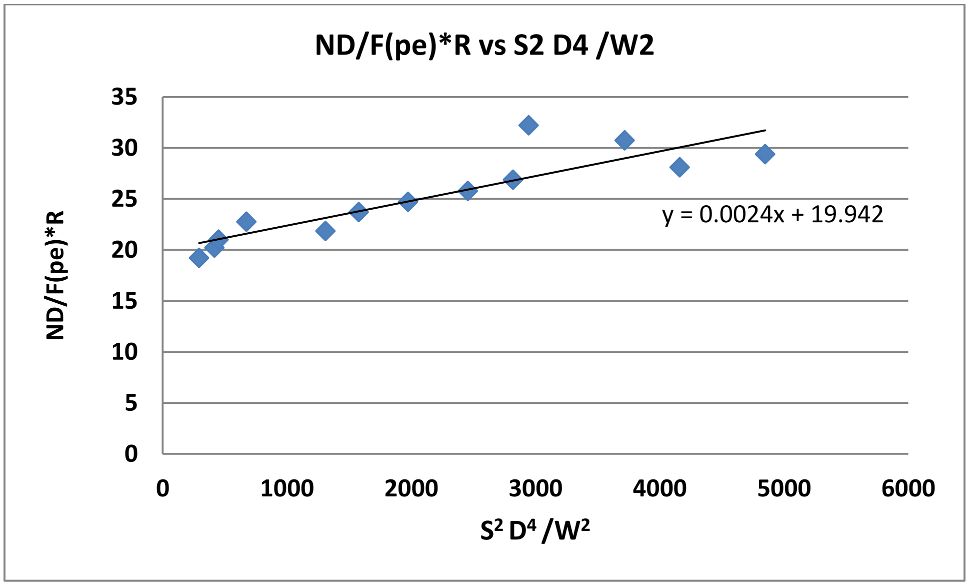

Figure 4.4 Determination of bit constants in 8.5″ section

As shown in Figure 4.4 the best straight line has a slope of 0.0024 and intercept of 19.942.

So a = 0.0024, b = 19.942, c was obtained by equation 5.1 and it has average value of 0.00089.

4.2.2 Bit Wear Coefficient

In order to determine the bit wear coefficient we should study the bit dull grading for the bit. The wear evaluation data for this section is shown on table 3.4 , The bit was graded as follow: 5 for the inner cutter structure (I), 5 for the outer cutting structure (O), BT : broken teeth and cutters for Dull characteristics (D) , A: all rows for location , 5 for the Bearing seals (B) , 1/16 for the gage , and HR: hours on bit for reason pulled (R) , since we are more interested in the cutting structure category, from the above data we can estimate overall average grade for this bit of 5 out of 8.

The calculated Wf value from the overall grade is 0.375, and since we have Wf value at the beginning which 1 (green bit) and 0.375 at the end of the bit run, by the iteration in equation 2.20 from the begging until the end we find the value of Wc = 5.5e-11.

4.2.3 ROP (Model & Actual) -8.5″ Section

After all the coefficients (bit, wear) were determined, the calculated ROP (model) and the actual ROP were plotted along the depth of main hole. Figure 4.5 shows the plot.

Figure 4.5 shows an acceptable match between the calculated ROP and the actual ROP obtained from the field. This shows the validity of the model with the coefficients obtained from data. Another plot of actual vs calculated ROP is shown in Figure 4.6.

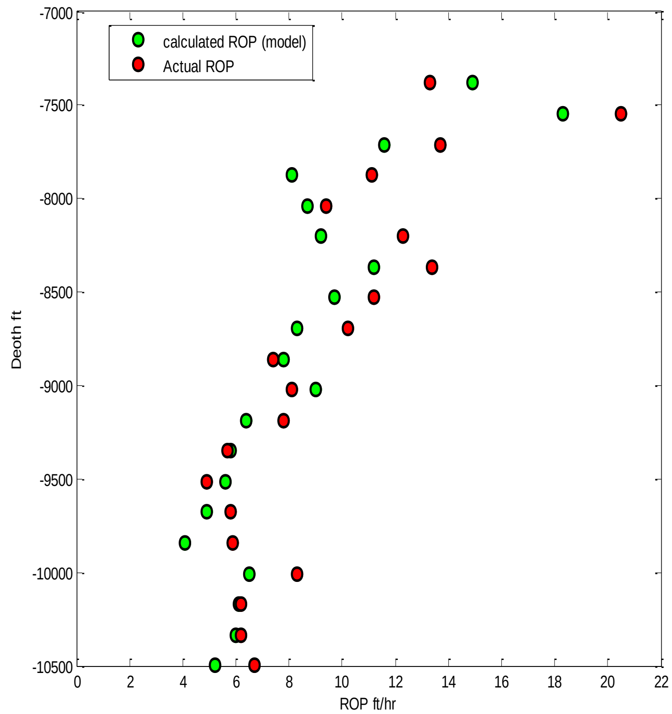

Figure 4.5 Comparison of calculated ROP and actual ROP (8.5″ section)

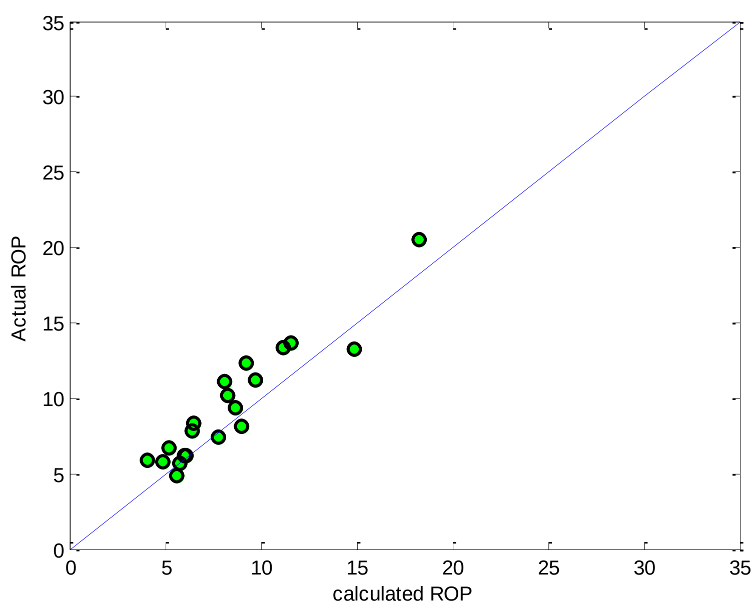

Figure 4.6 ROP model vs ROP actual (8.5″ section)

The plot in Figure 4.7 for the ROP (real vs calculated) for the entire well.

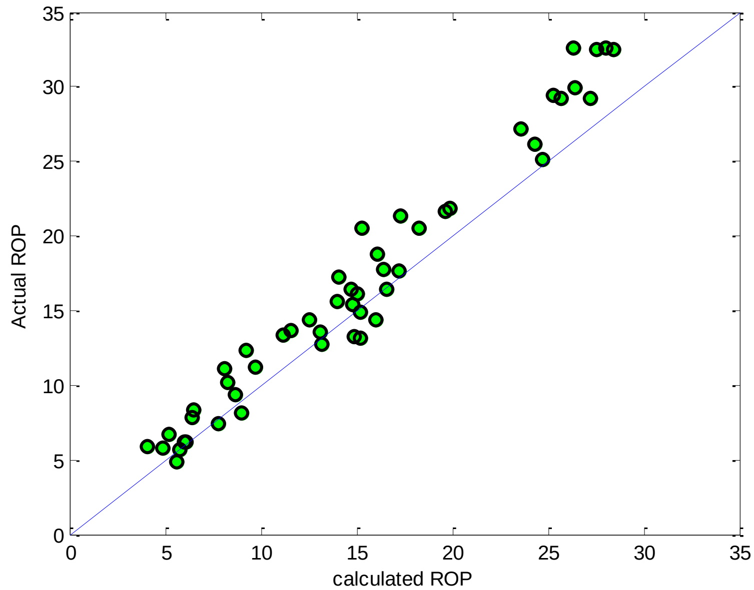

Figure 4.7 ROP actual vs ROP model (12.25″ & 8.5″ section)

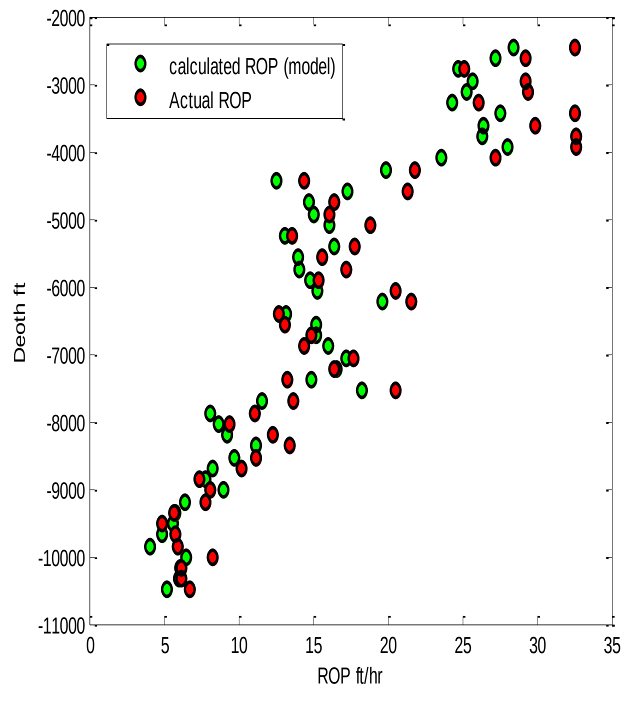

Figure 4.8 Comparison of calculated ROP and actual ROP (12.25″ & 8.5″ section)

CHAPTER 5

OPTIMIZATION ALGORITHM

5.1 Overview

In mathematics, computer science, or management science, mathematical optimization is defined as the selection of a best element (with regard to some criteria) from some set of available alternatives, it consists of maximizing or minimizing a real function (objective function) by finding the best inputs values in a defined domain that give the maximum or the minimum possible objective function value. Optimization problems can be complicated because of the nonlinearity and non-differentiability of the mathematical models and it can be divided in tow types, single objective optimization and multi objective optimization problems. In order to solve such problems researchers may use algorithms that terminate in a finite number of steps or iterative methods that converge to a solution (on some specified class of problems), or heuristics that may provide approximate solutions to some problems (although their iterates need not converge). However one of the efficient optimization algorithm types is Evolutionary algorithms and in this study, we use differential evolution.

The optimization technique called “Differential Evolution” was presented by Rainer Storn and Kenneth Price between 1994 to 1996, as outcome of their joint work during their attempt to solve a problem called “Chbychev Polynomial fitting problem", an idea made by Price to use vector differences for perturbing the vector population. Then both blossomed this idea and added many improvements, until the DE was successfully formulated and introduced [24-27].

The DE is a population based optimization technique and is characterized by its simplicity, robustness, few control variables and fast convergence. Being an evolutionary algorithm, the DE technique is suited for solving non-linear and non-differentiable optimization problems. DE is a kind of searching technique and requires number (NP) of candidate solutions (X_n^i) to form the population G_i , where each solution consists of certain number of parameters X_{nj} depending on the problem dimension.

$G^i = [X^i_1, X^i_2, \dots \dots, X^i_{NP}]$ i: generation , NP population size

$X_n^i = [x_{n1}, x_{n2}, \dots \dots, x_{nj}]$ n: problem dimension

The essential idea in any search technique depends on how to produce a variant (offspring) vector solution, on which the decision will be made, in order to choose the best (parent or variant). The strategy applied in this technique is to use the difference between randomly selected vectors to generate a new solution. For each solution in the original population, a trial solution is generated by performing process of mutation, recombination and selection operators. The old and new solutions are compared and the best solutions are moved to the next generation.

Initially the DE was developed to solve single objective optimization problem. The DE was compared against the well-known Particle Swarm Optimization technique [28], and the author has concluded that DE has better performance.

5.2 Optimization Procedure in DE for Single Objective Optimization Problem

The DE, as in any evolutionary technique, generally performs three steps: initialization, creating new trial generation and selection.

5.2.1 Initialization

As a preparation for the optimization process, the following requirements should be specified:

- Problem dimension which defines the number of control variables. Also, the range of each control element should be defined. This range is required during the process.
- NP: population size
- Number of iterations
- F: mutation factor.
- CR: Crossover factor, which determine probability for offspring parameters for each control vector.

Optimization using DE requires many steps, the first step is to generate initial population consisting of NP solutions or vectors, each vector contains the values of the various control variables which represent a candidate solution to the problem. This is done by assigning random values for each parameter of solution $\vec{x_j}$, within the range of the corresponding control variable.

$$x_{i,j} = x_{i,min} + random\,\#\left(x_{i,max} - x_{i,min}\right) \quad i = 1, D \;\; , j = 1, NP \tag{5.1}$$

5.2.2 Evaluation and Finding the Best Solution

Once the initial population is created, the objective value for each vector is calculated and then compared to get the best solution achieving the optimal objective. This value is stored externally and updated by comparison with all solutions in every generation.

5.2.3 Mutation

The mutation process is considered as the first step in the generation of new solutions. At this stage, for every solution (individual) in the population in generation-i: $X_i^{(G)}$ i = 1,NP, a mutant vector $V_i^{(G+1)}$ is generated using one of the following formulas:

$$V_i^{(G+1)} = X_{r1}^{(G)} + F\left(X_{r2}^{(G)} - X_{r3}^{(G)}\right) \tag{5.2}$$

$$V_i^{(G+1)} = X_{best}^{(G)} + F\left(X_{r1}^{(G)} - X_{r2}^{(G)}\right) \tag{5.3}$$

$$V_i^{(G+1)} = X_i^{(G)} + F\left(X_{best}^{(G)} - X_i^{(G)}\right) + F\left(X_{r1}^{(G)} - X_{r2}^{(G)}\right) \quad (5.4)$$

$$V_i^{(G+1)} = X_{r1}^{(G)} + F\left(X_{r2}^{(G)} - X_{r3}^{(G)}\right) + F\left(X_{r4}^{(G)} - X_{r5}^{(G)}\right) \quad (5.5)$$

where: $X_{r1}^{(G)}$, $X_{r2}^{(G)}$, $X_{r3}^{(G)}$, $X_{r4}^{(G)}$ $X_{r5}^{(G)}$ are randomly selected solution vectors from the current generation (different from each other and the corresponding X_i and $X_{best}^{(G)}$ is the solution achieving best value. F is a mutation factor and it takes values between 0 and 2. The factor F plays a role in controlling the speed of convergence.

5.2.4 Crossover

For better perturbation and enhancement in the diversity of the generated solutions, a crossover process is performed by DE. In this step, the parameters of the generated mutant vector and the corresponding solution vector i in the original population are copied to a trial solution according to a certain crossover factor CR Є [0,1]. For each parameter, a random number in the range [0, 1] is generated and compared with CR, and if its value is less than or equal to CR, the parameter value is taken from the mutant vector, otherwise, it will be taken from the parent. Crossover process is shown in Figure 5.1. However, in case CR was defined to be zero, then all the parameters of the trial vector are copied from the parent vector Xi, except one value (randomly chosen) of the trial vector is set equal to the corresponding parameter in the mutant vector. On the other hand, if CR is set equal to one. Then, all parameters will be copied from the mutant vector, except one value (randomly chosen) of the trial vector is set equal to the corresponding parameter in the parent vector. The factor 'CR' plays a role in controlling the smoothness of the convergence. As CR becomes very small, it becomes very probable that the trial solutions would have characteristic of their parent vectors and therefore, slow the convergence.

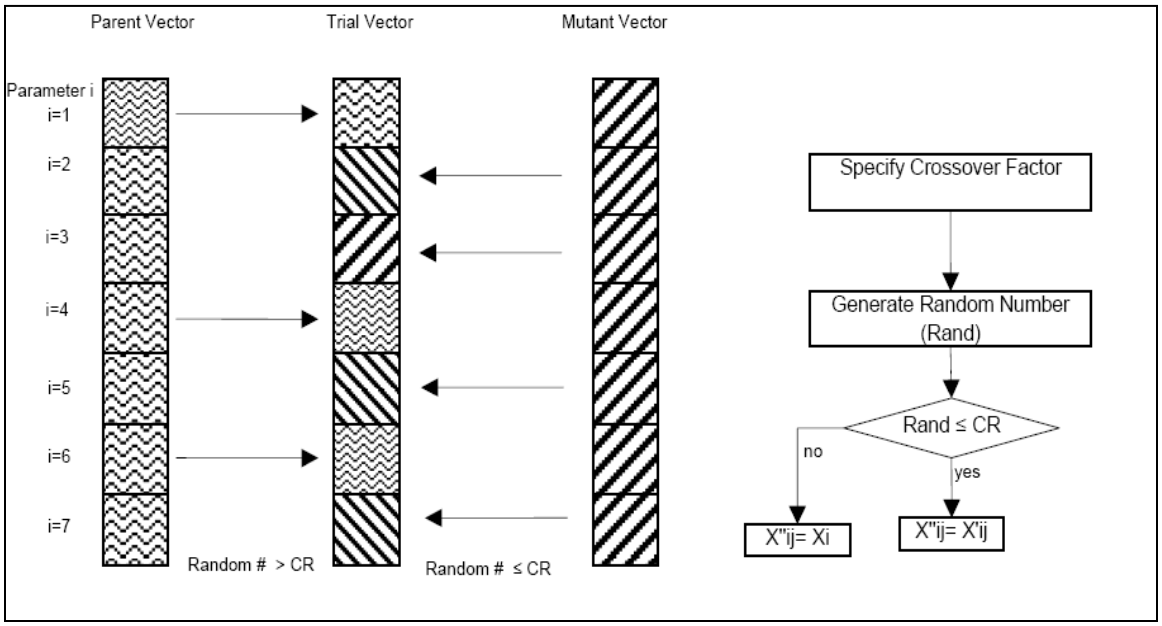

Figure 5.1 Crossover (Vesterstro and Thomsen)

5.2.5 Selection

The final step toward generation of a new population is to compare the solutions in old population and their corresponding trial solutions and then select the better one. For this, the objective value corresponding to each trial solution is calculated and compared with the value of the parent. If the new solution performed better it replace the parent, otherwise the old solution is retained.

5.2.6 Stopping Criteria

Once, a new generation is produced, the problem updates the global best. The user defined criteria would also be checked. In most cases a maximum number of iterations is defined and selected as stopping criteria. In practice, the user can check the results and verify the change and can determine when to stop.

Figure 5.2 shows a flow chart summarizing the procedure of DE as explained above.

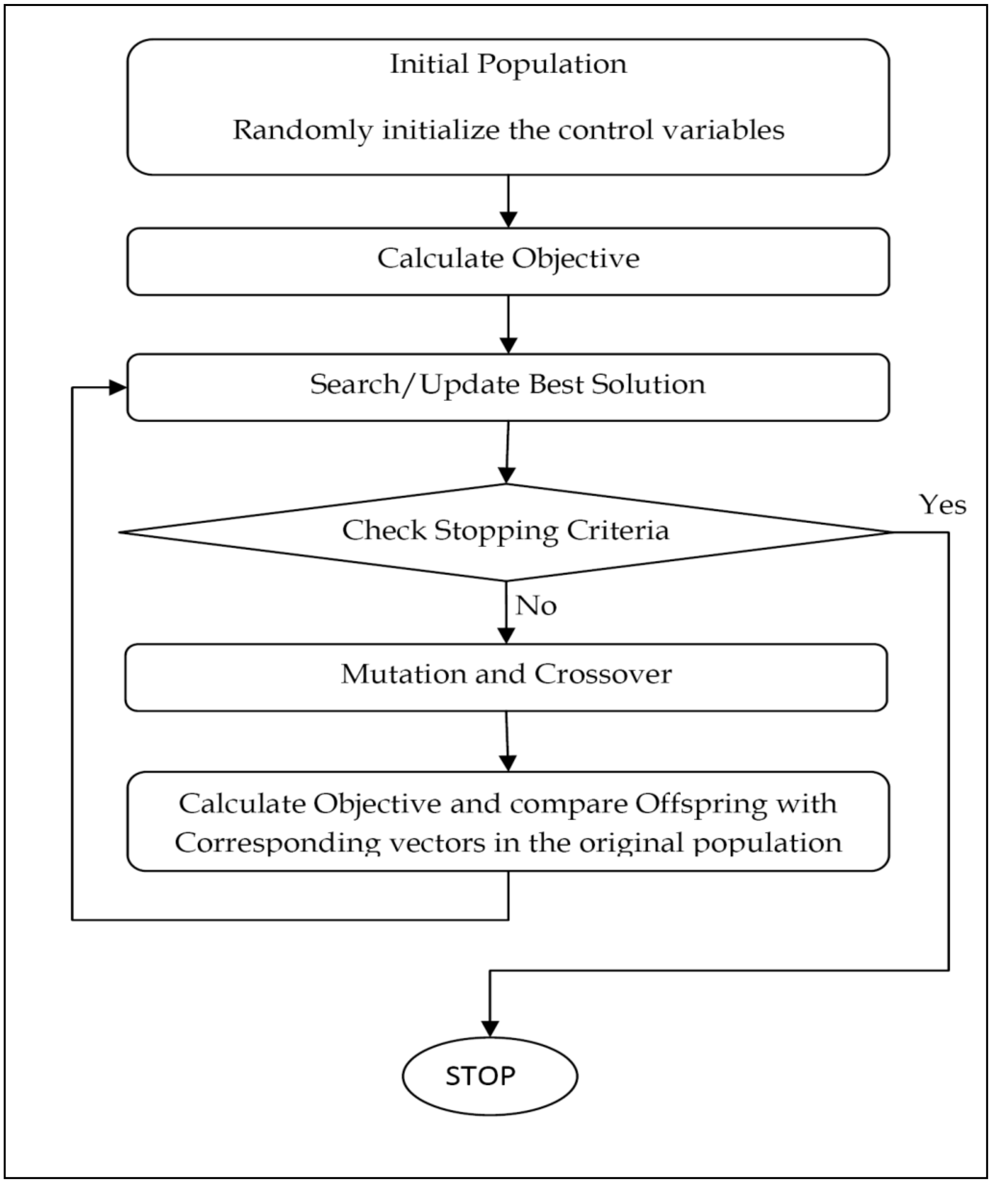

Figure 5.2 DE flowchart

5.3 Time Optimization

As mentioned earlier in the introduction of this study, this technique is used to find the optimum parameters that lead to minimize the drilling and the total time, hence the objective function is the time, and the parameters are WOB (weight on bit), N (rotation speed), and q (flow rate), below the requirements that should be specified as preparation for the optimization operation.

Control elements range

The lower and upper bound for each parameter should be defined

```
lx = [ql; Nl; Wl];  % lower bound
ux = [qu; Nu; Wu];  % Upper bound

ql = 500*ones(NIntervs,1);      % GPM units
qu = 600*ones(NIntervs,1);      % GPM , units
Nl = 60*ones (NIntervs,1);        %RPM , units
Nu = 90*ones (NIntervs,1);        %RPM ,untis
Wl = 6000*ones (NIntervs,1);     % Lbf , untis
Wu = 34100*ones (NIntervs,1);    % Lbf , untis
```

Problem dimension

The problem dimension which shows the number of control variables is 3

```
Lx = length (lx);       % Dimension of the problem
```

Population size

Population size Np is computed from

```
Np = 4 + floor(3 * log(dim));
```

floor ( ): is a function that rounds a number to its nearest integer towards minus infinity.

Number of iterations

Iteration number is computed from

```
Nt = ceil(Nfevs/Np);
```

Where:

Nfevs: the number of function evaluations which will be determined in the beginning of results chapter.

Ceil ( ): is a function that rounds a number to its nearest integer garter than it toward positive infinity.

Crossover factor

The crossover factor in this work is

```
F_CR = 0.95;
```

CHAPTER 6

RESULTS AND DISCUSSION

Many runs were made using MATLAB for the specific objective of optimizing the time required to drill a predetermined section.

In this chapter results are presented for:

1. Drilling time optimization (12.25″, 8.5″ sections)
2. Total time optimization (12.25″, 8.5″ sections)
3. WOB and Wf sensitivity analysis

6.1 Drilling time

The drilling time here is the time spent in the drilling process, without considering trips and reaming time.

The drilling time for the entire section here is given by this equation

$$Drilling\ Time\ = \sum_{i=1}^{n} \left(\frac{IL}{ROP}\right)_i \tag{6.1}$$

And for each interval is given by this equation

$$Drilling\ Time\ = \frac{Cons}{W_f\left[\, f_c(P_e)\left(\frac{aS^2 d_b^3}{N\,W^2}+\frac{b}{N d_b}+\frac{c d_b \gamma_f\, \mu}{F_{jm}}\right)^{-1}\right]} \tag{6.2}$$

The constant here is the interval length which is 164 ft.

This drilling time equation was set as the objective function in the optimization algorithm. The case of drilling time for two sections A: the intermediate section (12.25″ hole) and B: the main or production section (8.5″ hole) were studied.

A: The Intermediate Section (12.25″ Hole)

The data for this section has been presented in Chapter 3, The section extends from 700 m (2296 ft) depth to 2200 m (7216 ft) depth. Therefore the total length of this section is 1500m (4875 ft). The section is subdivided into thirty intervals, and the data points are collected each 50 meters.

Since differential evolution was used in this study, the number of function evaluation has great effect on achieving the best objective value which is the lowest drilling time in this case, many runs for different numbers of function evaluations were made in order to achieve the flattening of lines corresponding to the lowest objective value, and then set that number into the optimization algorithm as a stopping criteria.

The Figures 6.1 – 6.6 show the different cases of the N_{fevs}, the objective value on y axis and the N_{fevs} on x axis.

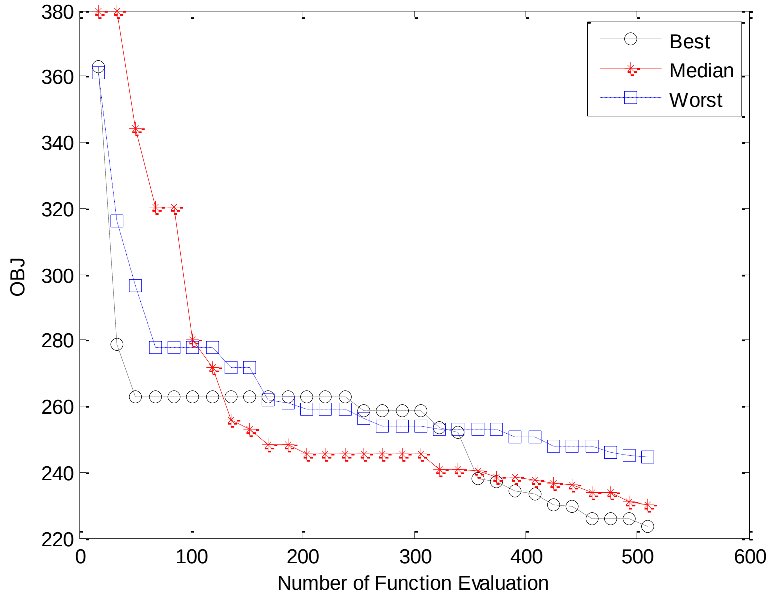

Figure 6.1 Nfevs = 500 drilling time (12.25″ section)

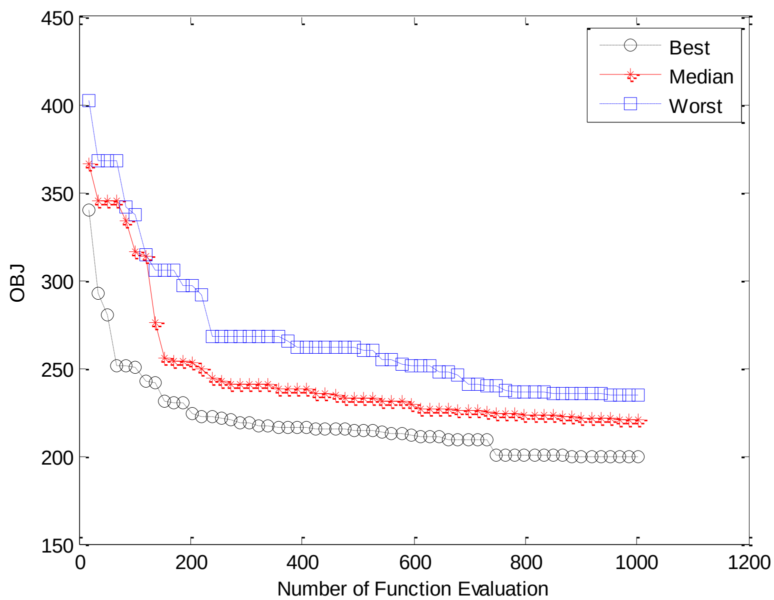

Figure 6.2 Nfevs = 1000 drilling time (12.25″ section)

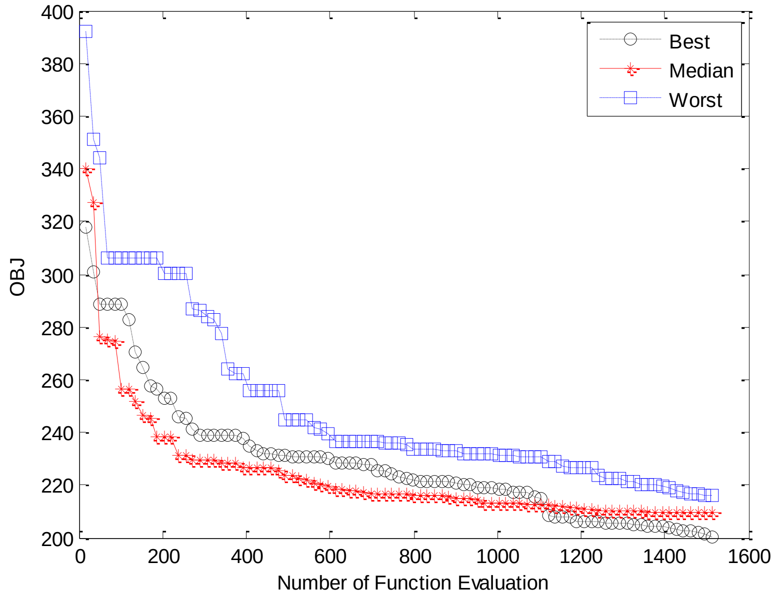

Figure 6.3 Nfevs = 1500 drilling time (12.25″ section)

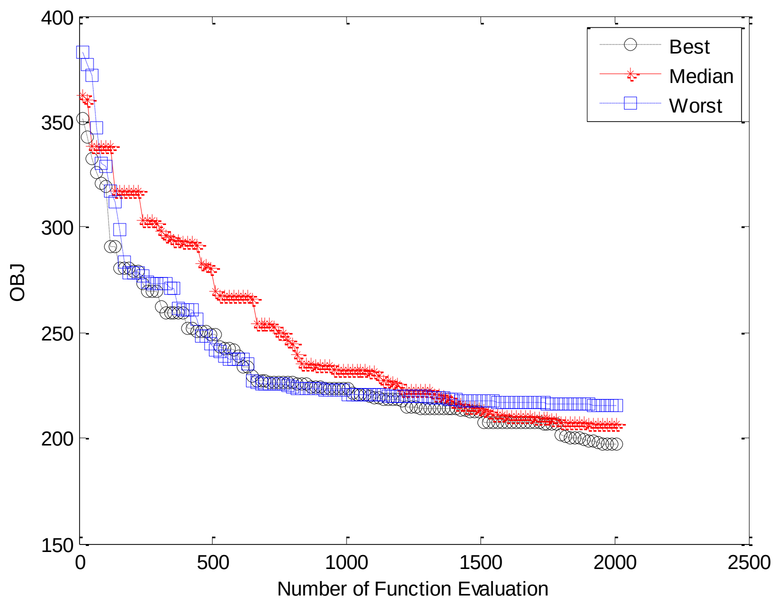

Figure 6.4 Nfevs = 2000 drilling time (12.25″ section)

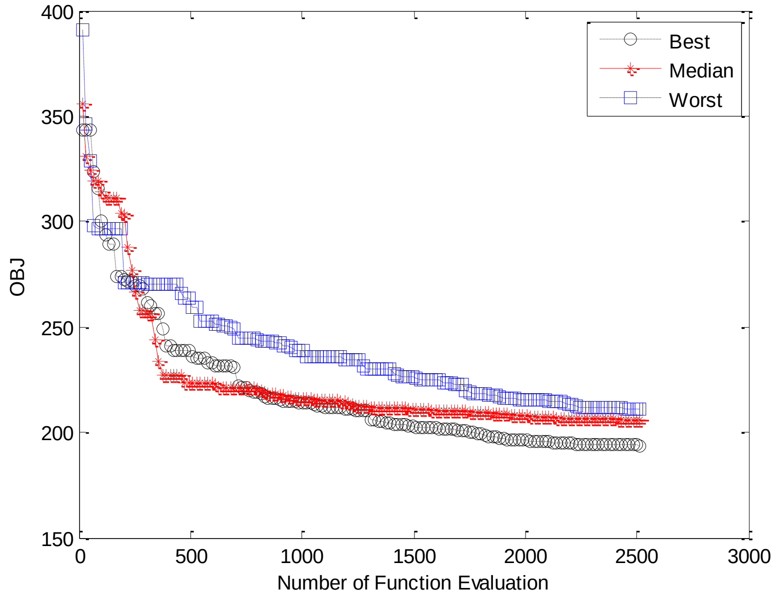

Figure 6.5 Nfevs = 2500 drilling time (12.25″ section)

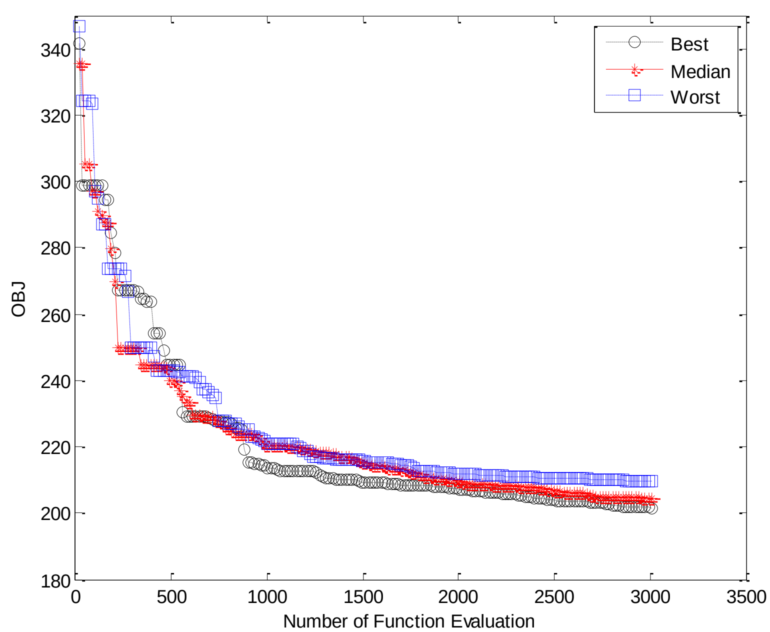

Figure 6.6 Nfevs = 3000 drilling time (12.25″ section)

As it is clear from Figure 6.6 the flattening of the three plots occurs at about N_{fev} = 3000. When the number increase beyond 3000, there is no considerable change on the value of the objective function and this will lead to more consumption in terms of time and space in computer programs. So 3000 was chosen as the N_{fevs} to be used in the optimization algorithm.

Figure 6.7 shows the difference between the optimized drilling time obtained from the optimized drilling parameters (flow rate, RPM, and WOB) and the actual drilling time measured during the drilling for each data point in the intermediate section.

Figure 6.7 shows that the optimized drilling time is smaller than the actual drilling time as measured on the field, this difference between these two increases as the depth increases. At the end of the section the total cumulative drilling time is about 251 hours (10.5 days) during actual drilling on field while the optimized drilling time as determined by the optimizer is 201 hours (8.3 days).

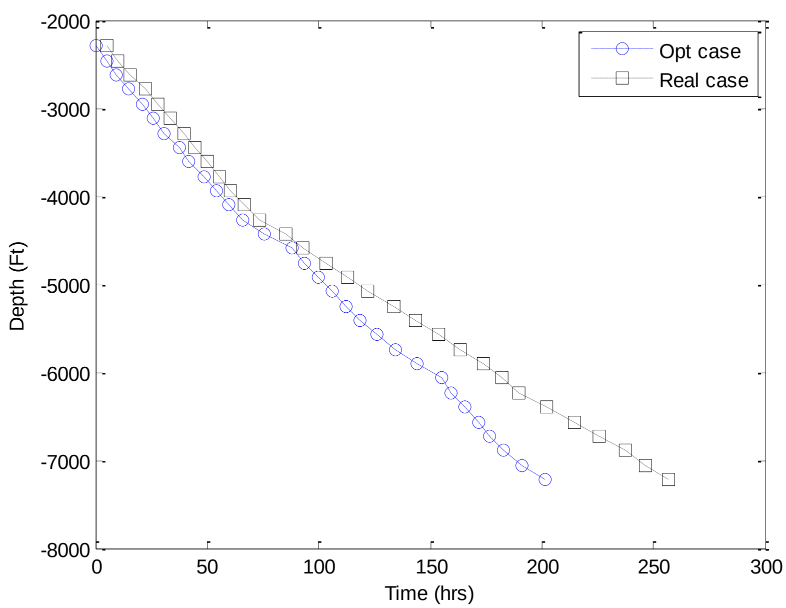

Figure 6.7 Drilling time of real case and optimized case (12.25″ section)

Therfore the same section can be completed with about 2.5 days ahead if the drilling parameters are optimized. This is about 21% reduction in the time needed to drill this borehole section.

Optimizing the drilling time here comes from optimizing the ROP through the drilling parameters (flow rate, RPM, WOB).

Figure 6.8 shows the actual ROP (red line) and optimized ROP (blue line).

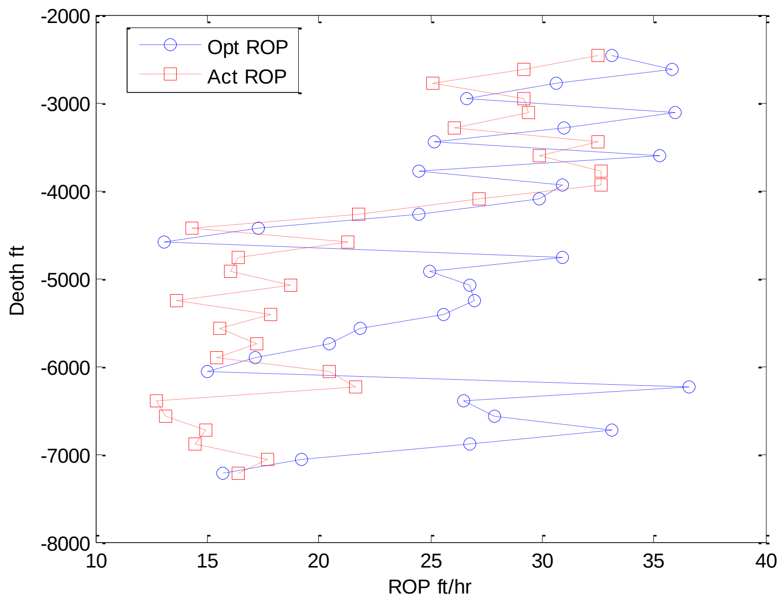

Figure 6.8 Real ROP and optimized ROP – drilling time (12.25″ section)

As it clear from Figure 6.8 that the optimized ROP values from the model are generally greater than the actual ROP values obtained during drilling. Hence, this difference has great impact in reducing the overall time required to drill the section.

Figure 6.9 to 6.11 show the optimized parameters values plotted against the depth for the intermediate section. The search ranges of the parameters in this part were taken from the

DDR and MLD, so that the values of the parameters obtained bounded by the lowest and highest values used in this section.

The parameters range in intermediate section shown in the Table 6.1.

Table 6.1 Parameters range in intermediate section

Parameters		Lower bond	Upper bound
Flow rate (GPM)		700	800
Rotation speed (RPM)		60	90
Weight on bit	(Lbf)	6744	31473
	(KN)	30	140
	(Ton)	3	14.27

These bounds have been set as constraints in the optimization algorithm.

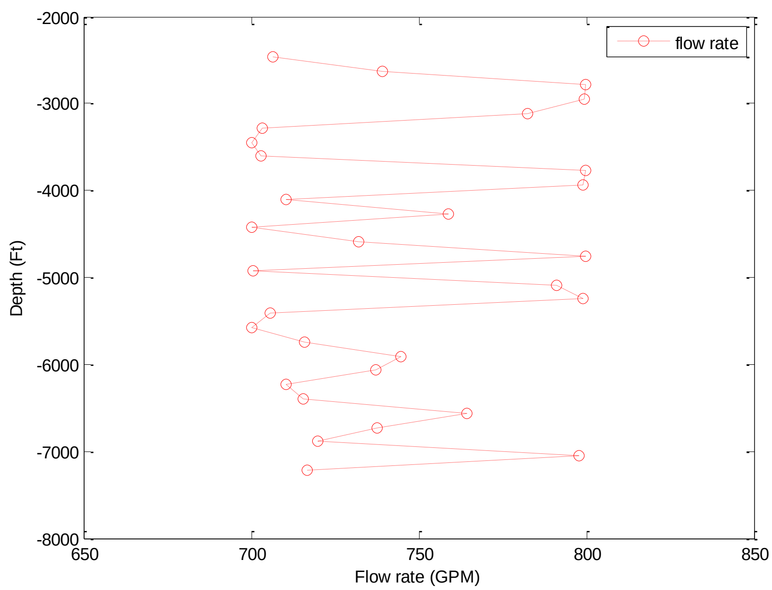

Figure 6.9 Optimized flow rate - drilling time (12.25″ section)

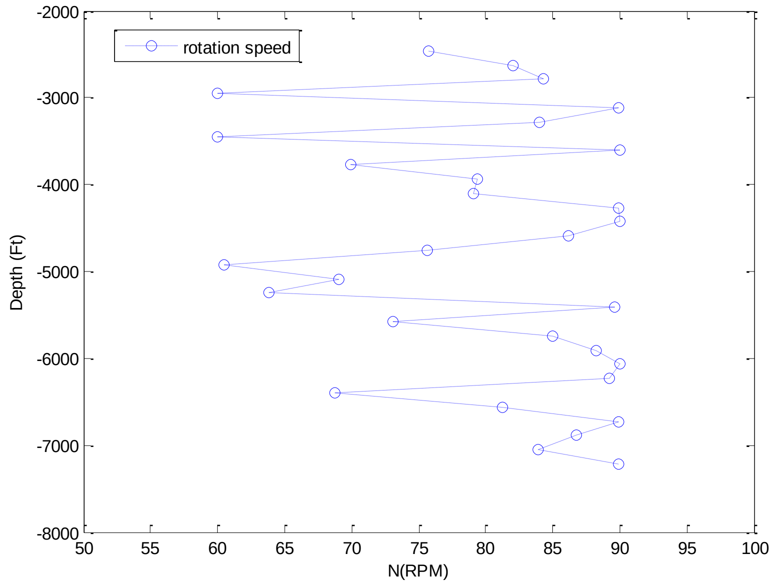

Figure 6.10 Optimized rotation speed– drilling time (12.25″ section)

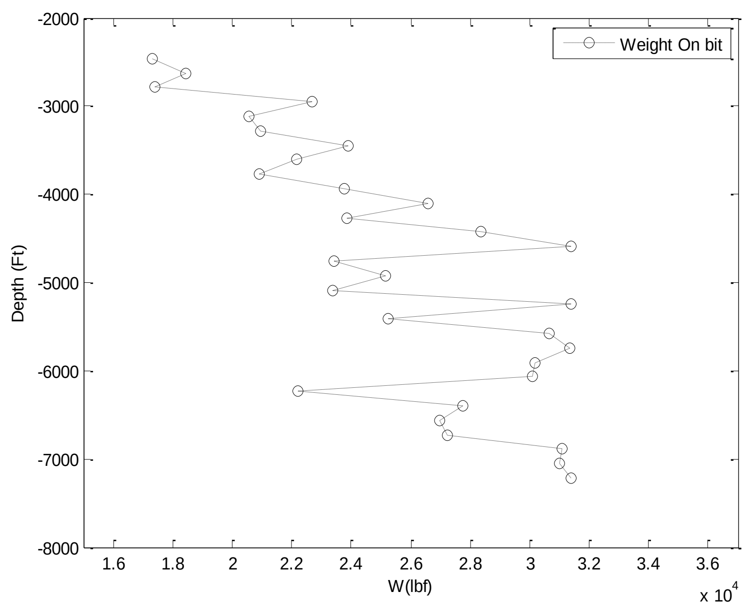

Figure 6.11 Optimized weight on bit-drilling time (12.25″ section)

Essential part of this study is paying attention to the bit wear condition, so through this work we are able to predict the wear status of the bit during the drilling, and accordingly we can determine at which depth we should pull the bit out to change it.

Figure 6.12 shows the plot of Wf versus depth.

The Wf value starts form 1 and decreases till the minimum Wf value at which the bit should be pulled out, It is clear from the figure that three bits have been used to drill the intermediate section whereas in the actual filed scenario four bits were used in the same section .

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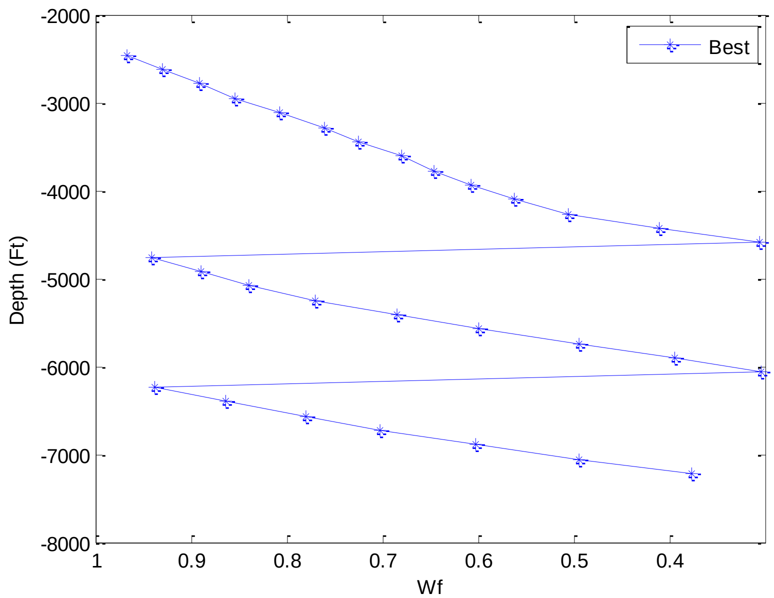

Figure 6.12 Wf vs depth- drilling time (12.25″ section)

B: The Main Section (8.5″ Hole)

In this section the drilling time was studied in the main hole (8.5 ″ hole), this section begins at 2200 m (7216 ft) and ends at 3200 m (10496 ft), so the total length is about 1000 m (3280 ft), the section subdivided into 20 intervals, so that the length of each interval was 50 m, other necessary data for this section has been presented in Chapter 3.

The number of function evaluations in the optimization algorithm plays a role in determining the desired objective function value, in this study the objective function which is the drilling time was minimized to achieve the minimum possible value, and this can be noticed when the lines start flattening as the number of function evaluation increases. So to determine the appropriate number of function evaluations, many runs were made with different values of N_{fev} values. The results of these runs are shown in Figures 6.13 to 6.18.

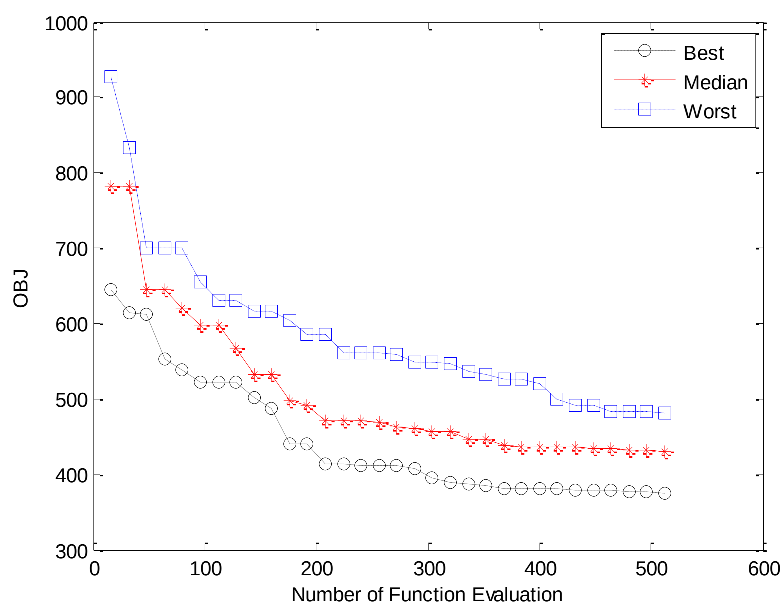

Figure 6.13 Nfevs = 500-drilling time (8.5″ section)

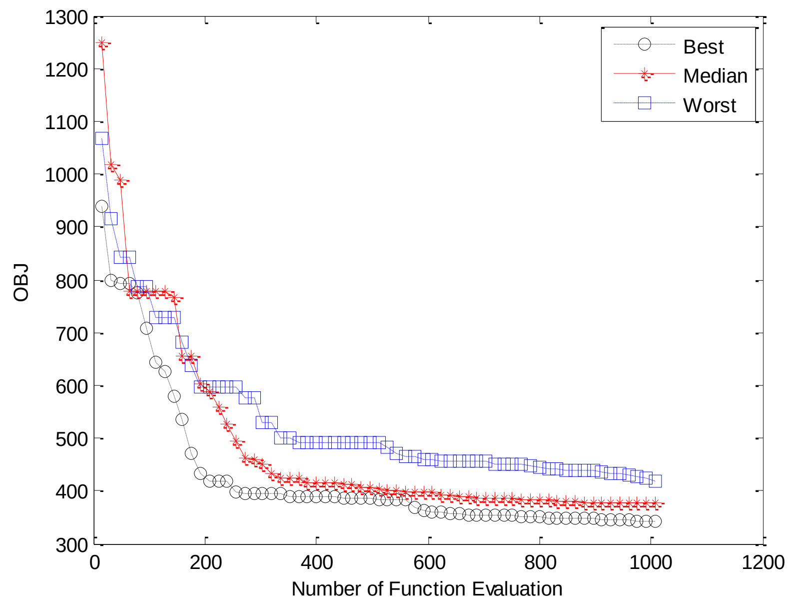

Figure 6.14 Nfevs = 1000-drilling time (8.5″ section)

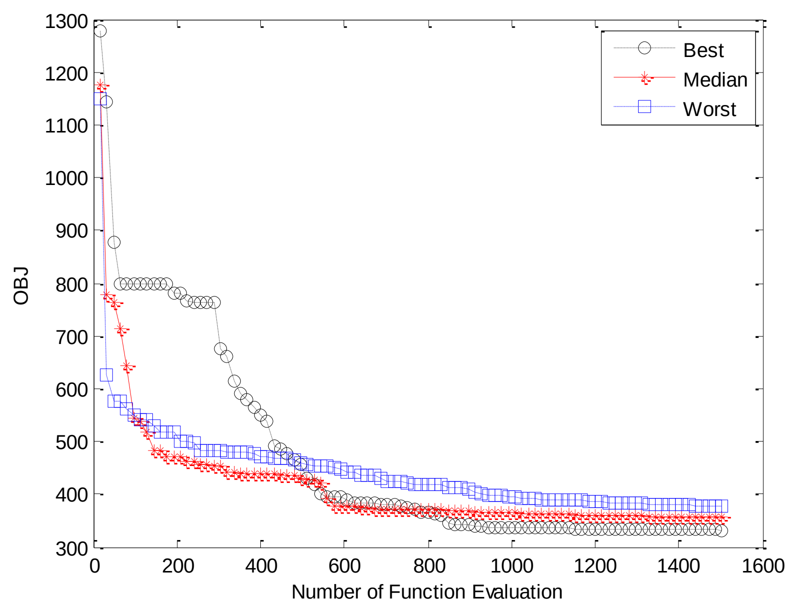

Figure 6.15 Nfevs = 1500-drilling time (8.5″ section)

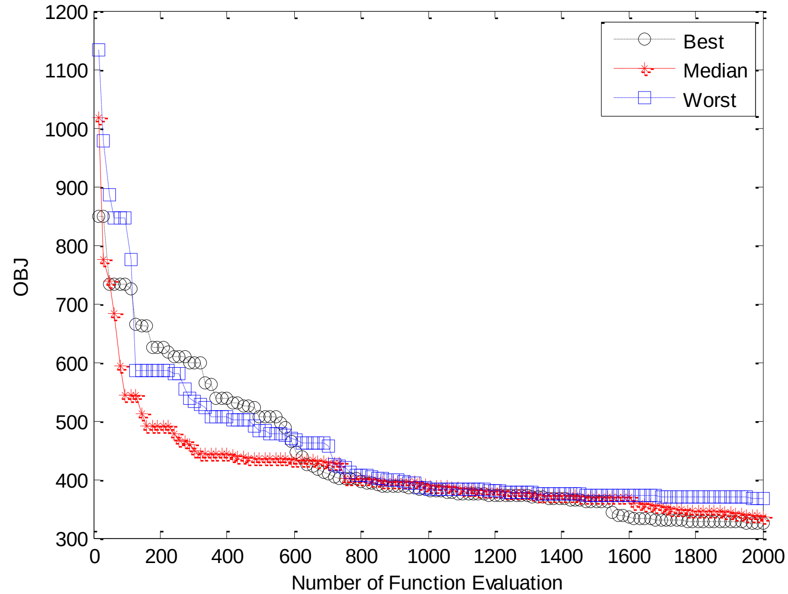

Figure 6.16 Nfevs = 2000-drilling time (8.5″ section)

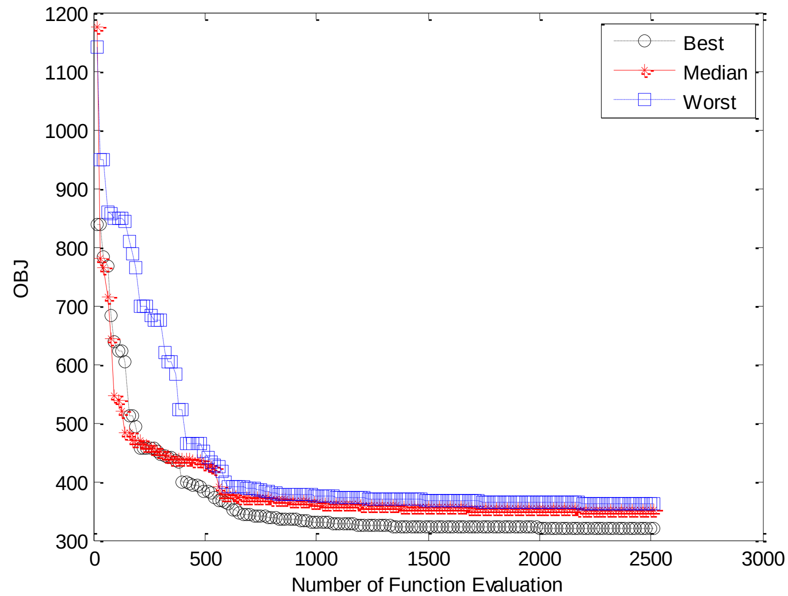

Figure 6.17 Nfevs = 2500-drilling time (8.5″ section)

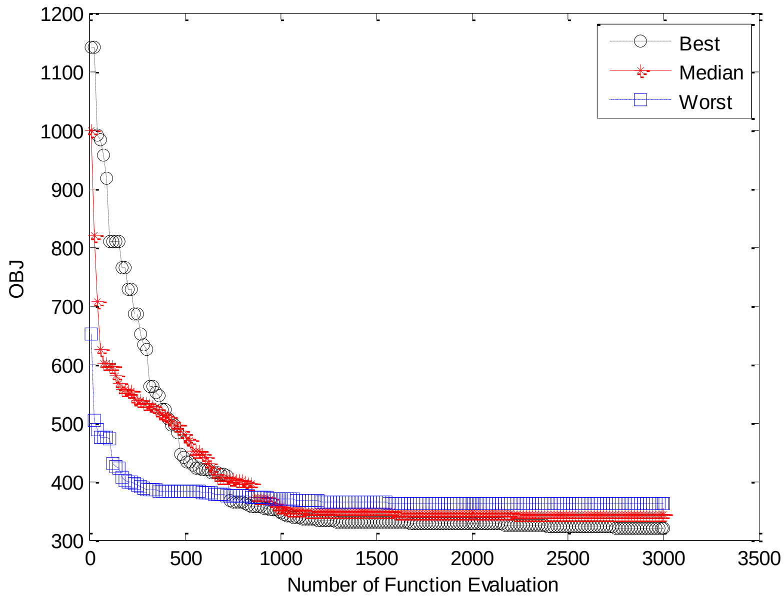

Figure 6.18 Nfevs = 3000-drilling time (8.5″ section)

From Figure 6.18 it is clear the minimum objective function value which is 320 hours or 13.5 days was achieved at about N_{fevs} = 3000, increasing N_{fevs} beyond this value will not add considerable effect on the objective function value. So this value has been set in the algorithm to perform the optimization.

MATLAB runs were made and the following results of the optimization process were obtanied .

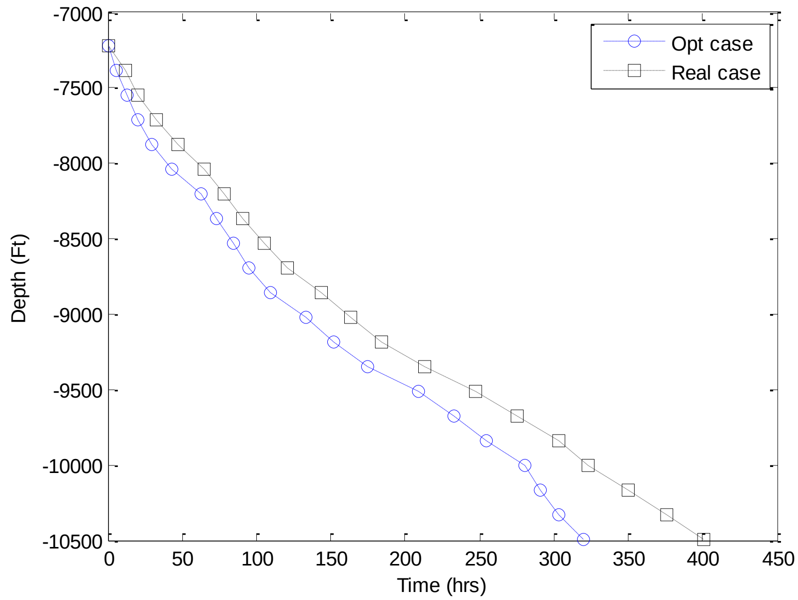

Figure 6.19 Drilling time of real case and optimized case (8.5″ section)

In the actual, the total vertical depth at 3200 m (10500 ft) was reached in 400.1 hours which is about 16.67 days, and this time was spent because of the low ROP in the deepest sections, whereas the optimized case took about 320 hours (13.3 days) to complete the same section, the difference between the actual case and the optimized case is 80 hours, so the optimization here leads to 3.3 days saving.

This reduction in the drilling time results from improving the ROP through the optimal choice of drilling parameters, Figure 6.20 shows the optimized ROP and the actual ROP.

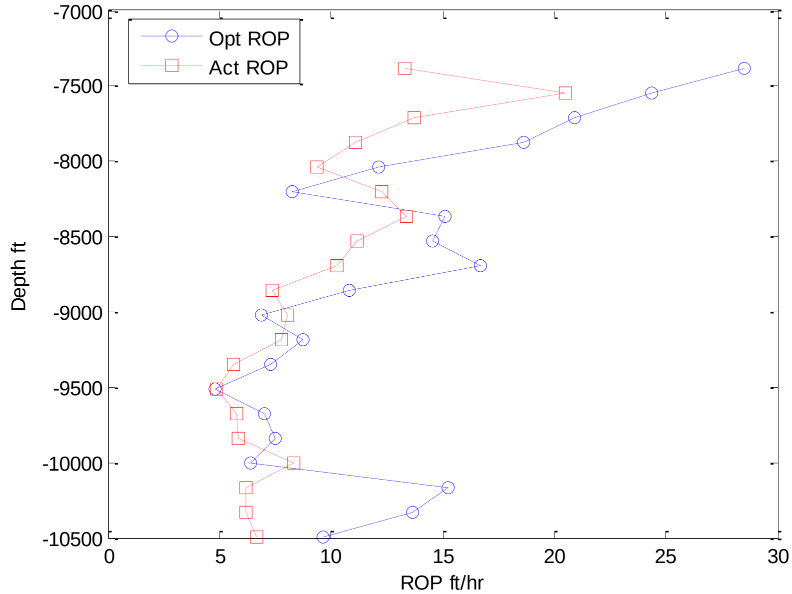

Figure 6.20 Real ROP and optimized ROP – drilling time (8.5″ section)

It is observed that greater ROP values are obtained in the most data points, and this increment achieved by the drilling parameters values result from the optimization. The Figures 7.21 to 7.23 show the three parameters values along the main hole, the ranges of the parameters in this part were taken from the DDR and MLD. The parameters ranges in the main section are shown on the Table 6.2.

Table 6.2 Parameters range in the main section

Parameters		Lower bond	Upper bound
Flow rate (GPM)		500	600
Rotation speed (RPM)		60	90
Weight on bit	(Lbf)	6000	34100
	(KN)	26.7	151.68
	(Ton)	2.7	15.46

These bounds have been set as constraints in the optimization algorithm

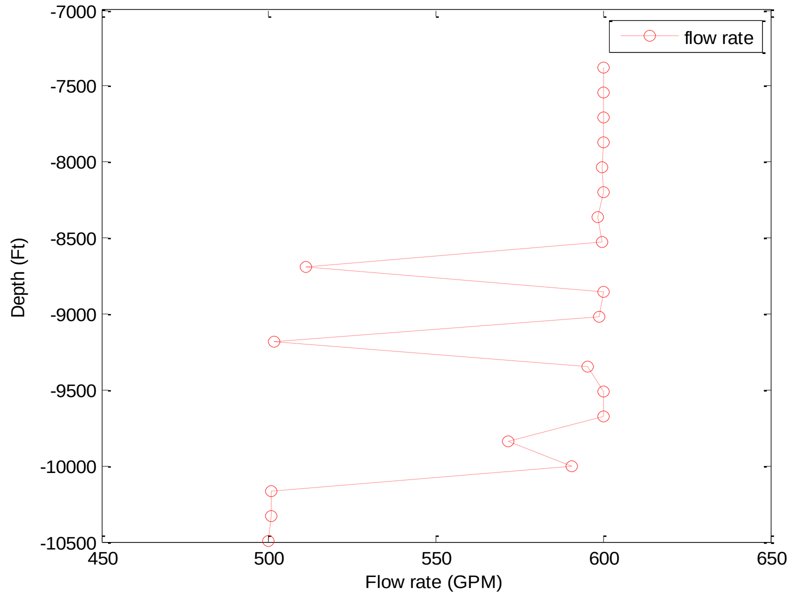

Figure 6.21 Optimized flow rate-drilling time (8.5″ section)

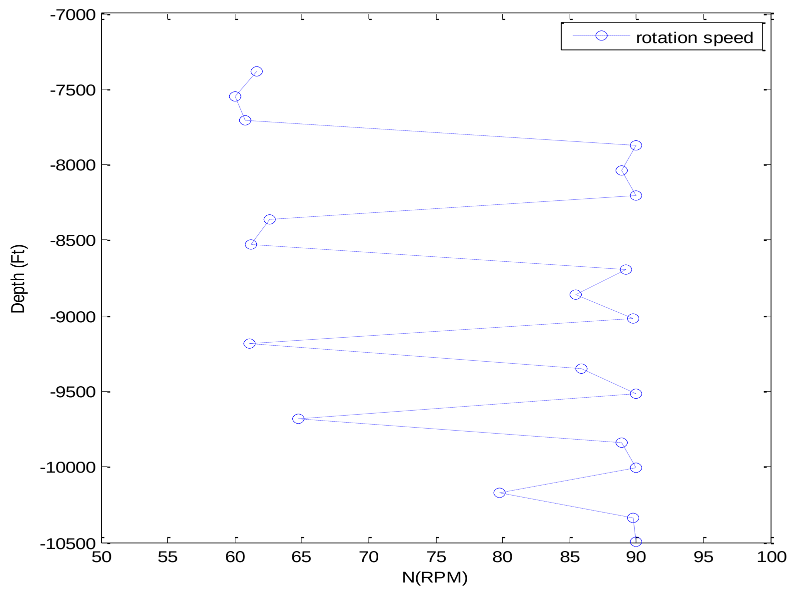

Figure 6.22 Optimized rotation speed– drilling time (8.5″ section)

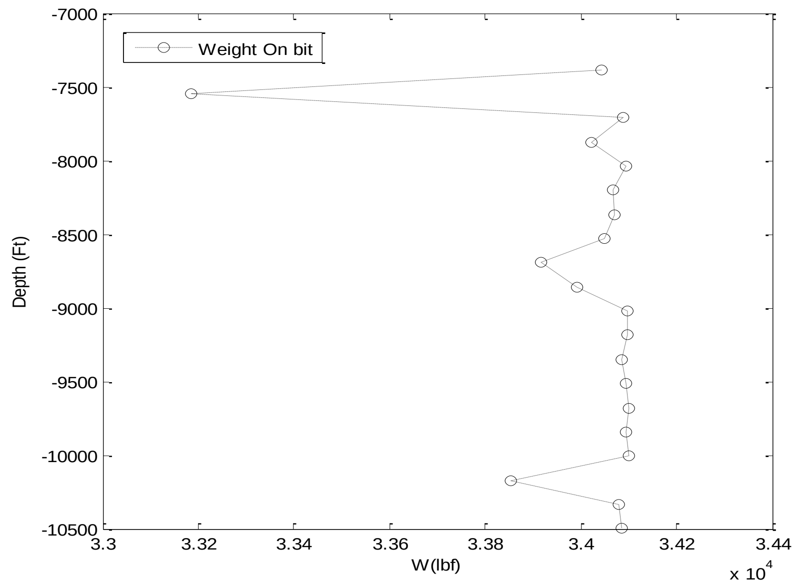

Figure 6.23 Optimized weight on bit-drilling time (8.5″ section)

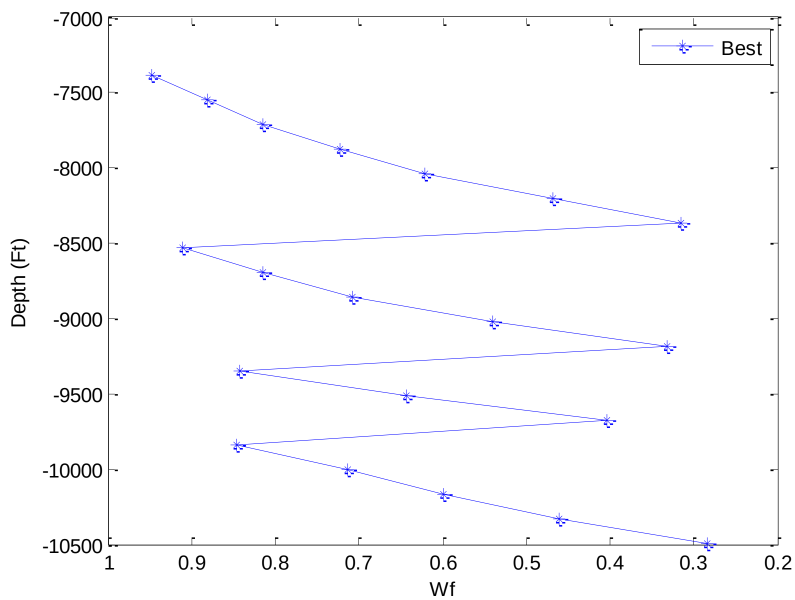

Figure 6.24 Wf vs depth- drilling time (8.5″ section)

Figure 6.24 shows the variation of the wear factor with the depth as drilling proceeds. It is evident that the bit is pulled out and replaced whenever the wear factor falls to about

0.25. In figure 6.24, the bit replaced three times to completely drill the section. Therefore the figure shows 4 bits and three trips.

Hence, by performing the optimization the time and the number of the bits used for drilling were reduced. This can save considerable amount in the total cost of drilling this section.

6.2 Total Time

As mentioned earlier, the definition of the total time in the drilling operation is the time consumed to drill entire section, this time includes the drilling time, the circulation and survey time, the trips time (round trip or wipe trip) and the reaming time. The non-productive time (NPT) is excluded here. The NPT is the time at which drilling operation is ceased, the time spent on repair, stuck pipe, fishing operation, hole problems, etc.

Therefore the objective function for the total time is

$$Total\ Time = \sum_{i=1}^{n} \left(\frac{IL}{ROP}\right)_i + \sum_{b=1}^{nb-1} (Trips\ time)_b + \sum_{b=1}^{nb-1} (Bit\ Change\ time)_b \quad (6.3)$$

Where

$$ROP = W_f \left[f_c(P_e) \left(\frac{aS^2 d_b^3}{N\, W^2} + \frac{b}{N d_b} + \frac{c d_b \gamma_f\, \mu}{F_{jm}} \right)^{-1} \right] \quad (6.4)$$

A: Total time - intermediate section (12.25″ hole).

The upper and lower bounds of parameters presented in Table 6.1 were used in this section. These values have been determined from experience and practices in this filed. Therefore these ranges of parameters have been extracted from the actual reports. By referring to operational parameters recommended by the bit manufacturer, it is possible to exceed the upper limit of these ranges up to specific values according to the bit type and specifications, but in some cases, the entire work space of the recommended parameters can not be applied due to the rig capacity, specifications, and some deficiencies.

In this research the DDR parameters ranges, and recommended operational parameters provided by one of the biggest bits manufacturers were studied.

The operational parameters recommended by the manufacturer are determined according to the size, name and code given to each bit, this code consists of letters and numbers belonging to IADC classification system. However, the recommended operational parameters sheet for the bits used in this well has been obtained.

The series number and type of the bits used in the intermediate section (12.25″) with the recommended parameters are shown on the operational parameters sheet. By referring to that sheet, the bits used in this section have the following recommended parameters shown in Table 6.3.

Table 6.3 Recommended operational parameters - intermediate section

Bit size	Series and type	Recommended operational parameters				
		Normal bit weight （KN/mm）	Rotary speed (rpm)	Total revolutions (10000r)	Recommended make-up torque for bit shank (KN.m)	Reg. API shank (in)
12-1/4”	MD117GLMC	0.30---0.90	300−−−60	20～45	37.9---43.3	6-5/8”
	HJ437GC	0.35---0.90	280---60	20~70	37.9---43.3	6-5/8”
	HA427GC	0.35---0.90	140---70	15~70	37.9---43.3	6-5/8”
	HA427GC	0.35---0.90	140---70	15~70	37.9---43.3	6-5/8”

The normal bit weight in the sheet is given in KN/mm, so the upper and lower values should be multiplied by the bit size in mm unit to get the WOB parameter values in KN. by using the conversion factor of 1 KN=224.809 lbf , the values in Lbf were obtained.

Thus 0.30 -- 0.90 KN/mm range is equivalent to 20984.8 lbf -- 62954.39 lbf, and the upper limit of the WOB for this type of bits is 62954.39 lbf, and because the WOB has the great influence on the ROP. We shall study the cases of increasing the upper limit from 31400 lbf to about 60000 lbf.

A.1: DDR and MLD parameters range.

In this part the constraints in the optimization algorithm were set according to the ranges extracted from the reports. These are presented on table 6.1.

We checked for the number of function evaluations required to give the best objective function value. Figures 6.25 to 6.30 show different N_{fevs}.

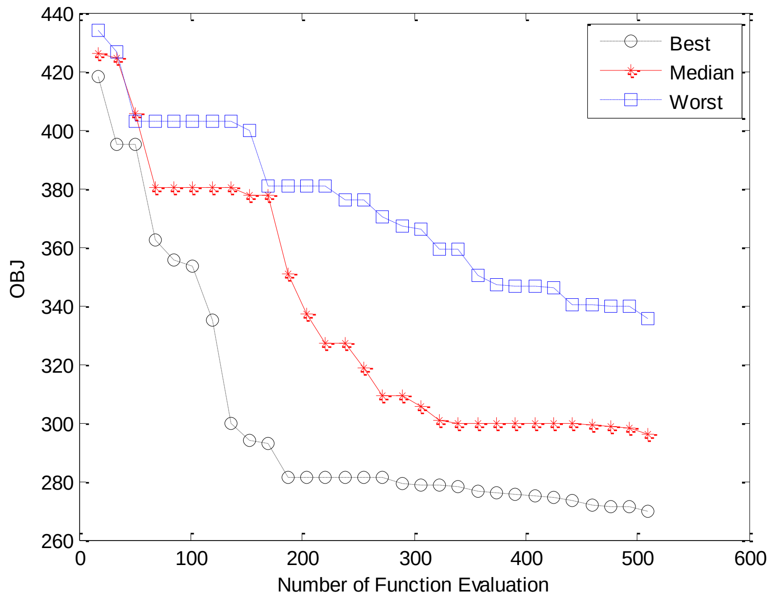

Figure 6.25 Nfevs = 500 total time (12.25″ section)

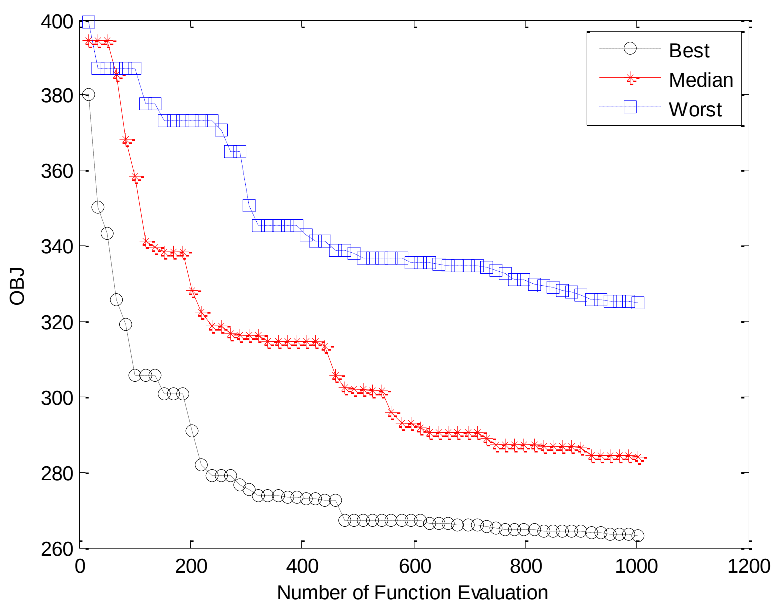

Figure 6.26 Nfevs = 1000 total time (12.25″ section)

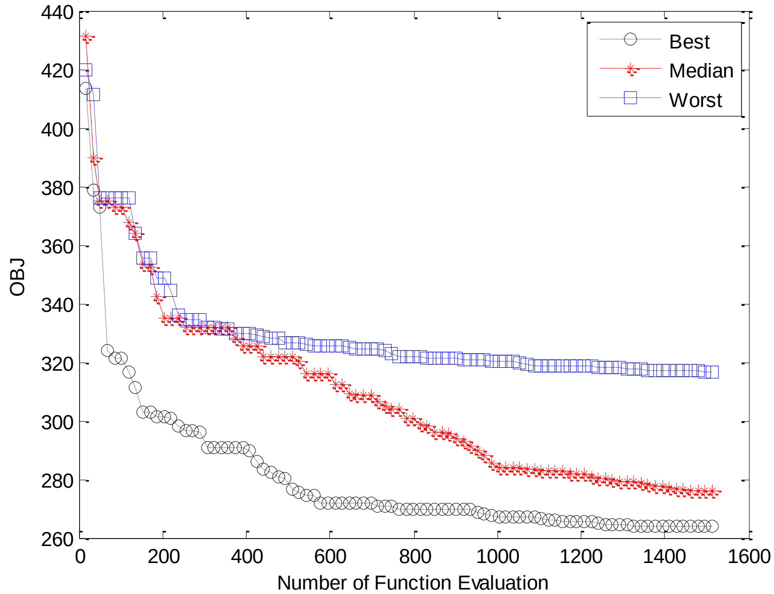

Figure 6.27 Nfevs = 1500 total time (12.25″ section)

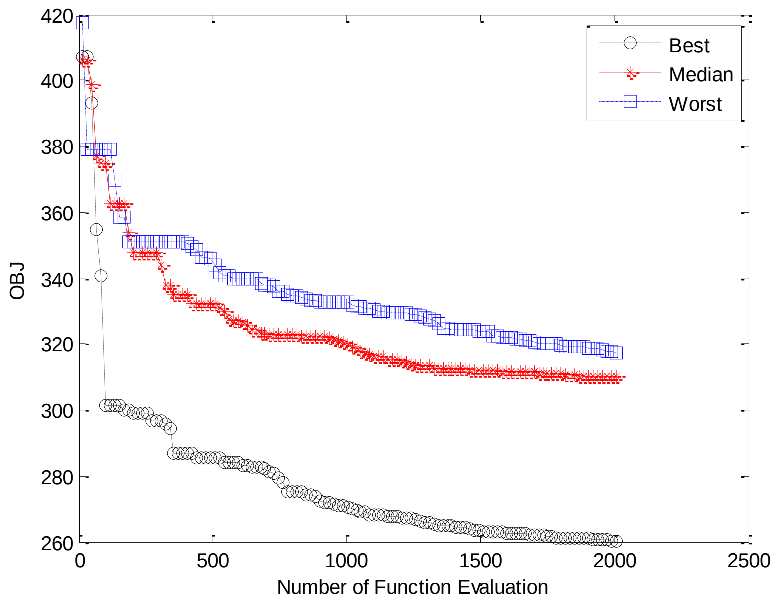

Figure 6.28 Nfevs = 2000 total time (12.25″ section)

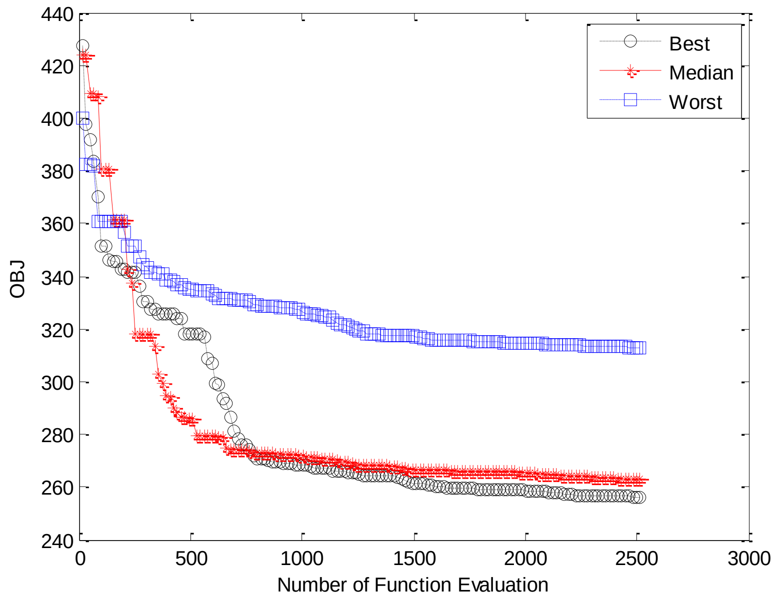

Figure 6.29 Nfevs = 2500 total time (12.25″ section)

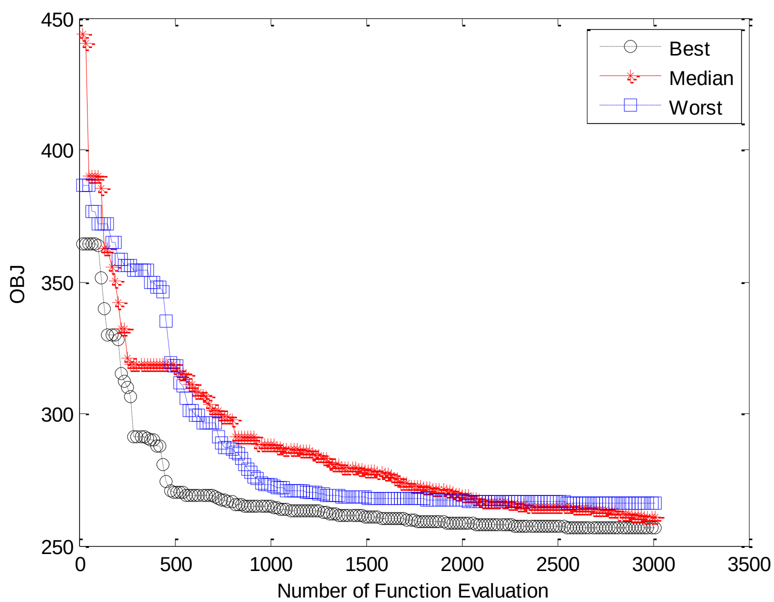

Figure 6.30 Nfevs = 3000 total time (12.25″ section)

Figure 6.30 shows that the flattening of the three plots, best, median and worst occurs at N_{fev} = 3000. Therefore 3000 has been set as the number of function evaluations in the case of optimizing the parameters to achieve the lowest total time, increasing beyond this value will not add major improvement in the objective value.

The main objective of this optimization is to reduce the total time through optimizing the drilling parameters, MATLAB run was made in order to optimize the three parameters mentioned previously. Figure 6.31 shows the difference between the optimized total time and the actual total time recorded while drilling.

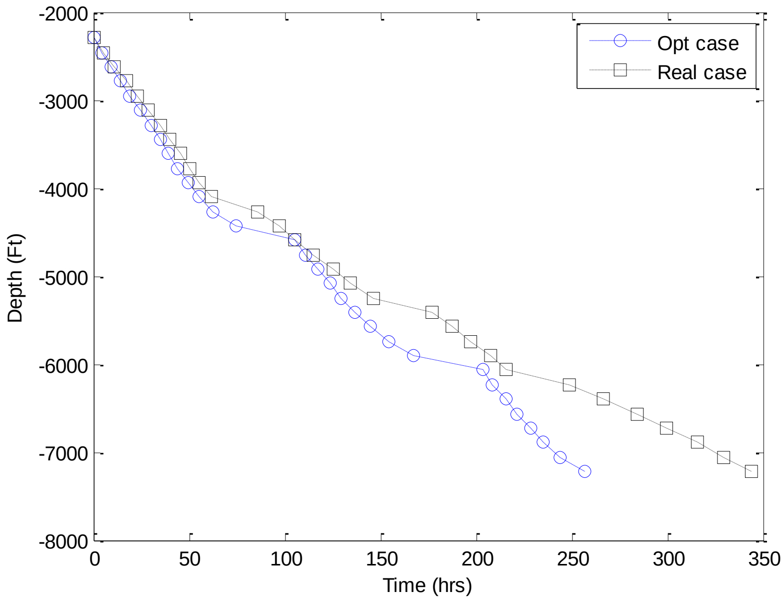

Figure 6.31 Total time of real case and optimized case (12.25″ section)

The total time of the intermediate section recorded in the field is 350 hours, almost 14.5 days. However the total time computed from the optimized parameters is 250 hours or 10.4 days. Therefore 4 days would be gained ahead of the actual. This represents about 28 % saving from the actual total time, consequently this reduction in time has great impact on the total cost of the well.

Since time is computed from ROP and the depth drilled, this reduction in time is achieved by improving in the ROP trough optimizing the drilling parameters, the improved ROP and the field ROP are shown in Figure 6.32. Also, figures 6.33, 6.34 and 6.35 show the optimized parameters, flow rate, rotation speed and the weight on bit respectively.

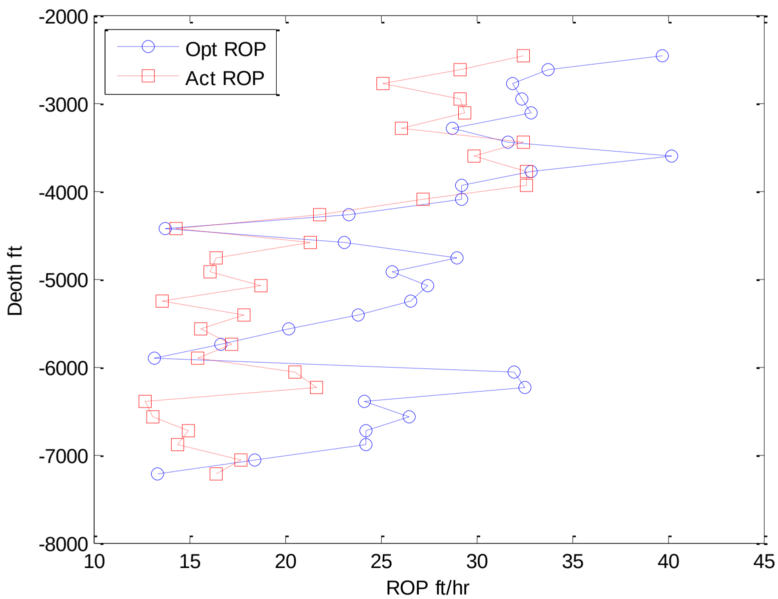

Figure 6.32 Real ROP and optimized ROP – total time (12.25″ section)

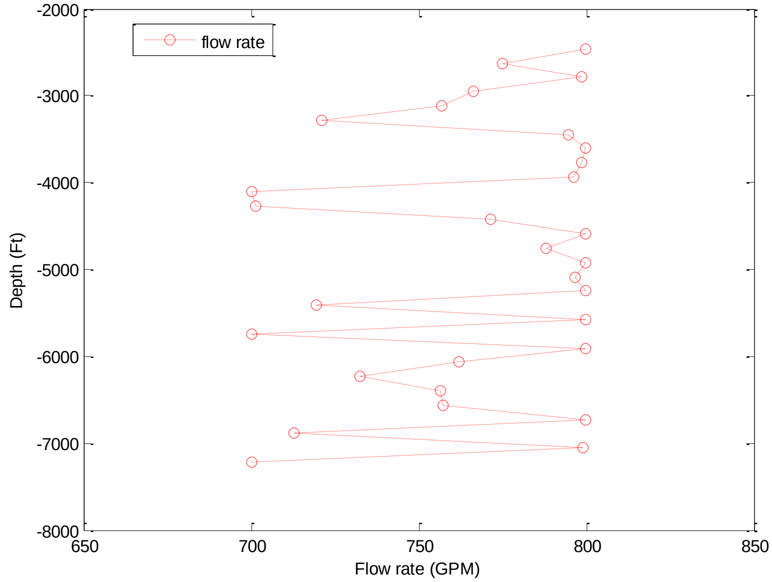

Figure 6.33 Optimized flow rate-total time (12.25″ section)

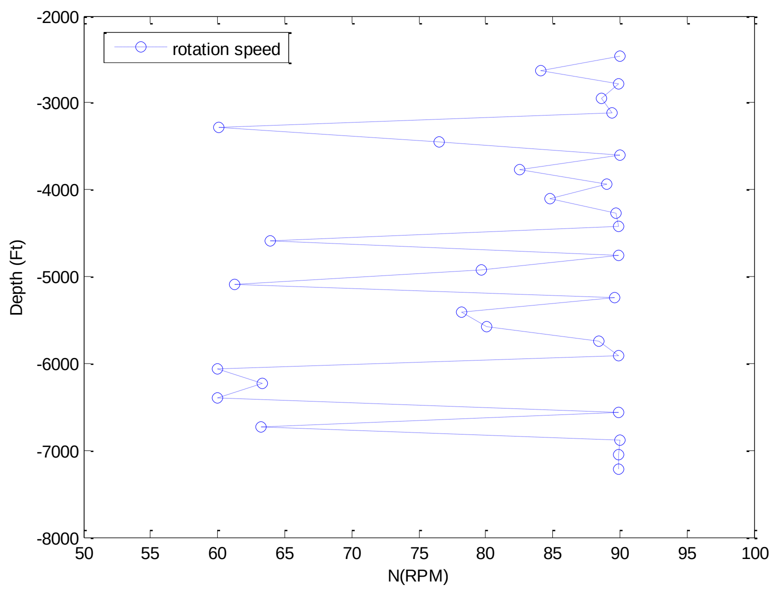

Figure 6.34 Optimized rotation speed– total time (12.25″ section)

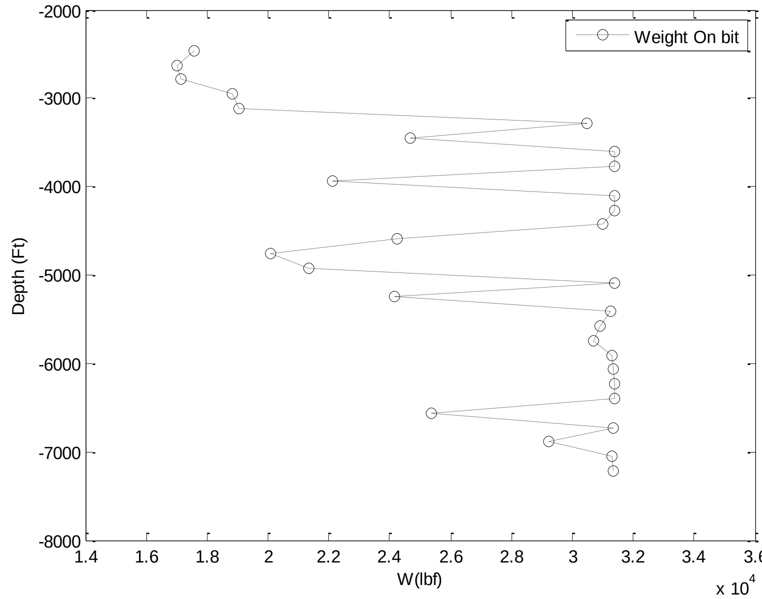

Figure 6.35 Optimized weight on bit-total time (12.25″ section)

As mentioned earlier, one of the objectives of this research is to study the effect of drilling parameters on the bit wear. The bit wear is represented by the Wf which starts from 1 for the new bit and decreases to the minimum value at which more time is consumed with marginal progress in the drilling rate. Figure 6.36 shows the plot of Wf vs depth.

Three bits were used. We can see the points at which Wf goes from small value (close to 0.25) to big value (close to 1). This is the point at which the worn-out bit is replaced by a new bit. New bits have wear factor value of 1.

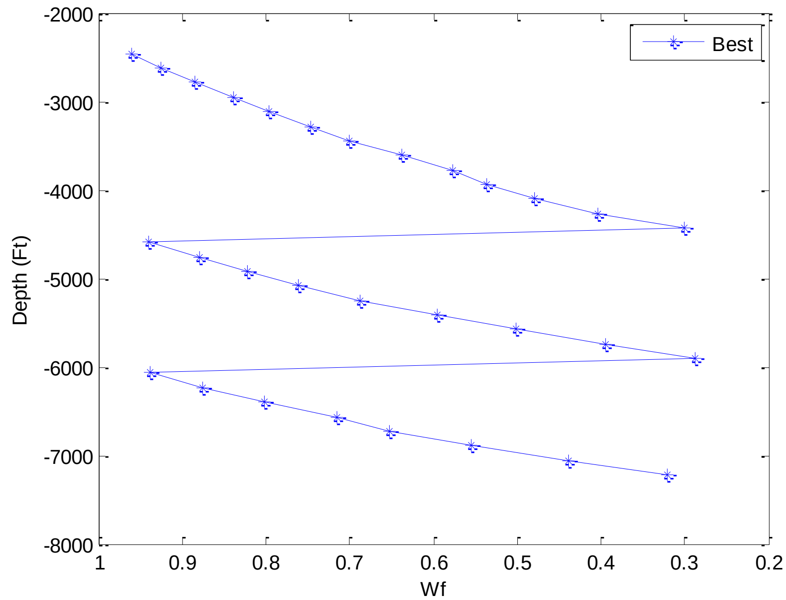

Figure 6.36 Wf vs depth- total time (12.25″ section)

One of the aims of the study is to show that the high ROP doesn't necessarily mean getting lesser total time. This is because high ROP requires in some points high values of drilling parameters which accelerate the bit wear process and this will require more trips to change the bit and consequently more time.

In the total time optimization, the algorithm was set to test the lower and upper bounds of the WOB, RPM and flow rate to see the effect of using these boundary values on the total time.

Here many cases were studied. The first applies the operating range from DDR and MLD. The second case involves increasing the upper bounds of the WOB up to the upper bound of the recommended operational parameters which is presented in part A.2

Applying the upper bound of the parameters in the algorithm leads to the result in Figure 6.37.

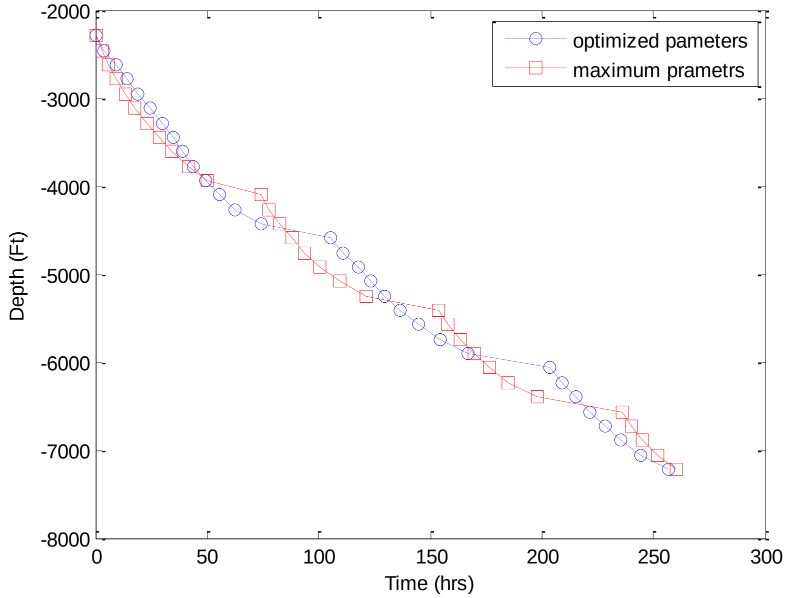

Figure 6.37 Total time (6744-31400 lbf)

Figure 6.37 shows the time from optimized parameters and the time from upper bounds of the parameters. The total time from the optimized parameters is less than that from upper bounds at the end of this section but this difference is very small, However 3 bits were used with optimum parameters instead of 4 bits with highest values of parameters. Hence the cost is reduced as well and it is expected to see considerable difference in the total time in the deepest section where the trips take more time.

A.2: Recommended operational parameters.

In this part, investigation on using higher values of WOB according to the recommended operational parameters sheet was performed, because the WOB has the great effect on the ROP.

The increase in the WOB is gradual, so the cases for many ranges of WOB were studied.

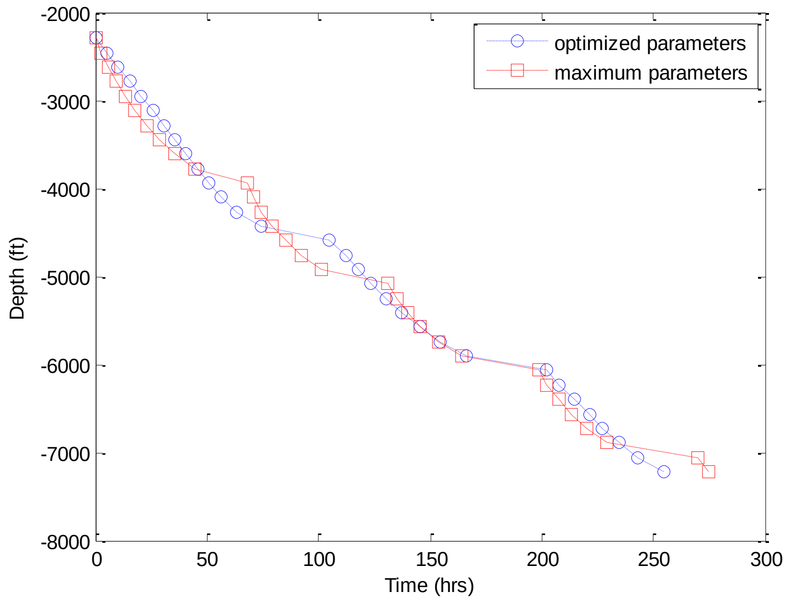

Figure 6.38 Total time -12.25″ section (6744-35000 lbf)

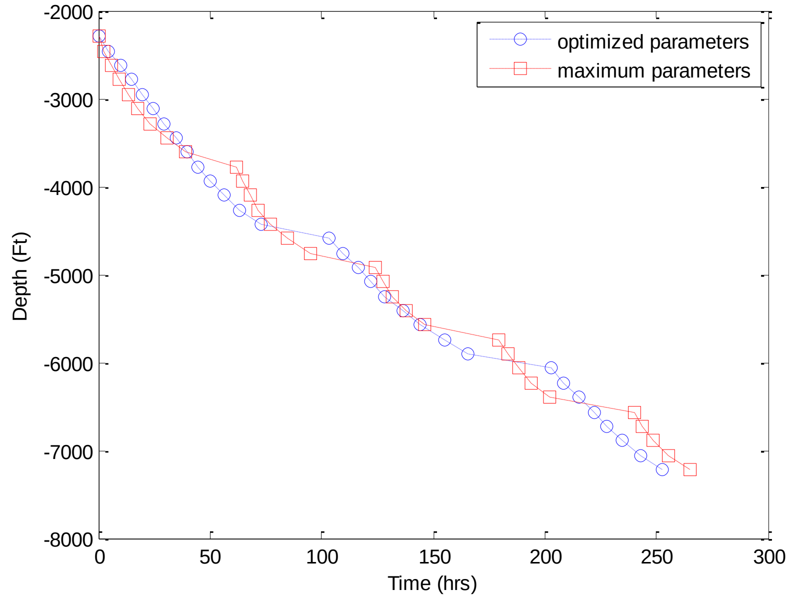

Figure 6.39 Total time -12.25″ section (6744-40000 lbf)

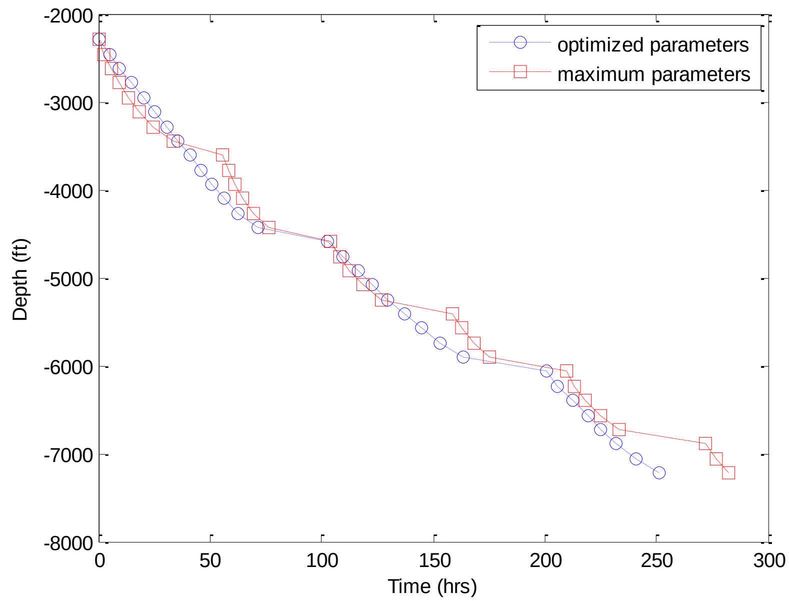

Figure 6.40 Total time-12.25″ section (6744-45000 lbf)

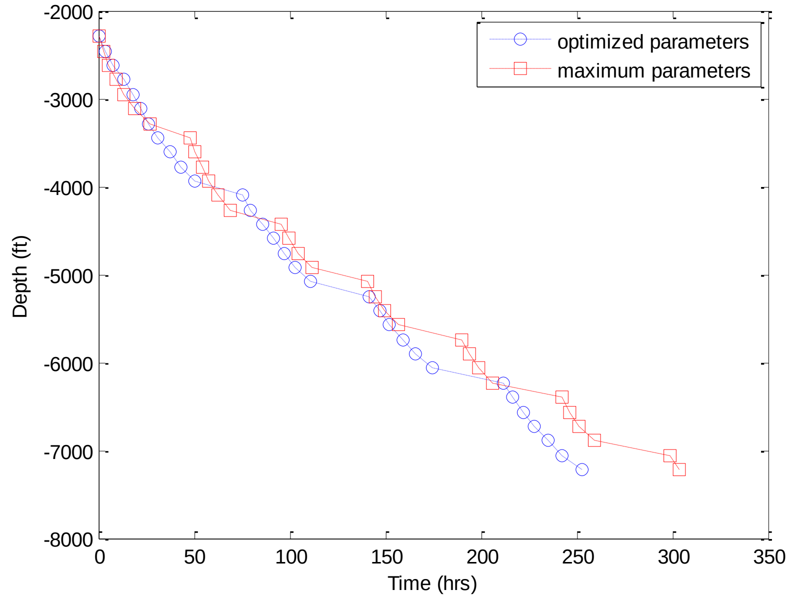

Figure 6.41 Total time-12.25″ section (6744-50000 lbf)

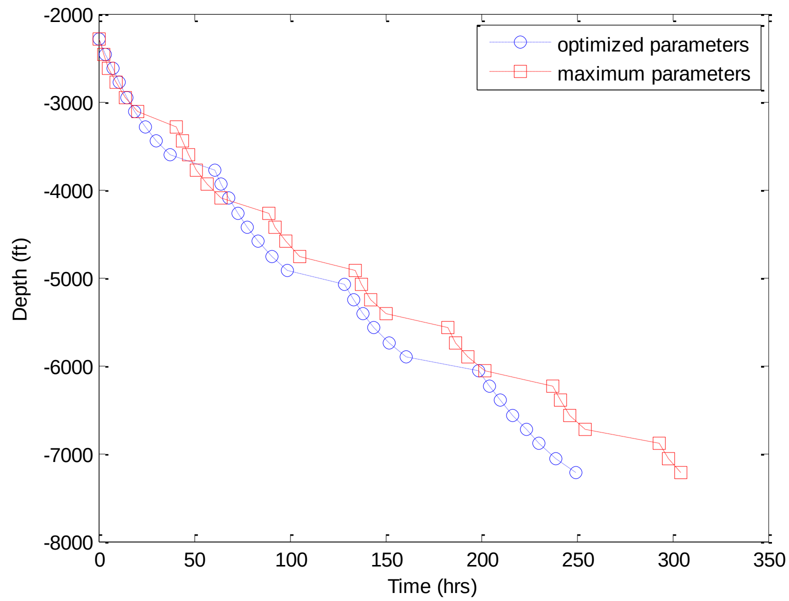

Figure 6.42 Total time -12.25″ section (6744-55000 lbf)

Figures 6.38 to 6.42 show that increasing the upper value of the WOB has great impact in reducing the total time in some parts but at the end of the section, the time obtained from the optimum parameters is less than the time obtained from the maximum parameters values and this difference is up to 2.2 days in Figure 6.42.

B: Total time - the main section (8.5″ hole)

In this section the same upper and lower bounds that were presented in Table 6.2 was used. These upper and lower parameters values have been extracted from the actual reports of the well. Also recommended operational parameters sheet for this section was obtained and the effect of increasing the upper limit of the WOB from the reports value to the bit manufacturer values on the total time was analyzed. Further, a comparison between the total time from the upper bounds of the parameters and the total time obtained from optimum parameters values are carried out.

As mentioned earlier the manufacturer's parameter ranges are specified according to bit size, name and the code of IADC classification system. However Table 6.4 shows the recommended operational parameters for the bits used in the main section.

Table 6.4 Recommended operational parameters – main section

Bit size	Series and type	Recommended operational parameters				
		Normal bit weight （KN/mm）	**Rotary speed (rpm)**	**Total revolutions (10000r)**	**Recommended make-up torque for bit shank (KN.m)**	**Reg. API shank (in)**
8-1/5”	HA527GC	0.35---1.05	120---50	15～45	16.3---21.7	4-1/2”
	HJ437GC	0.35---0.90	280---60	20~80	16.3---21.7	4-1/2”

The normal bit weight in the sheet is given in KN/mm, so the upper and lower values should be multiplied by the bit size in mm unit to get the WOB parameter values in KN , then by using the conversion factor of KN=224.809 lbf , we get the values in Lbf.

Thus, 0.35 -- 0.90 KN/mm range is equivalent to 16987.692 lbf -- 43682.637 lbf and hence the upper limit value of the WOB for this type of bits is 43682.637 lbf. Because the WOB has a great influence on the ROP, cases of increasing the upper limit from 34100 lbf to 45000 lbf was studied.

B.1: DDR and MLD parameters range.

In this part the lower and upper limits values in the actual drilling reports in the main section were set as bounds constraints in the optimization algorithm.

Since the objective function changed to include the tripping and the circulation time the number of function evaluations needed to achieve the best objective value should be determined. Therefore runs were made with different N_{fevs} and the results are presented below.

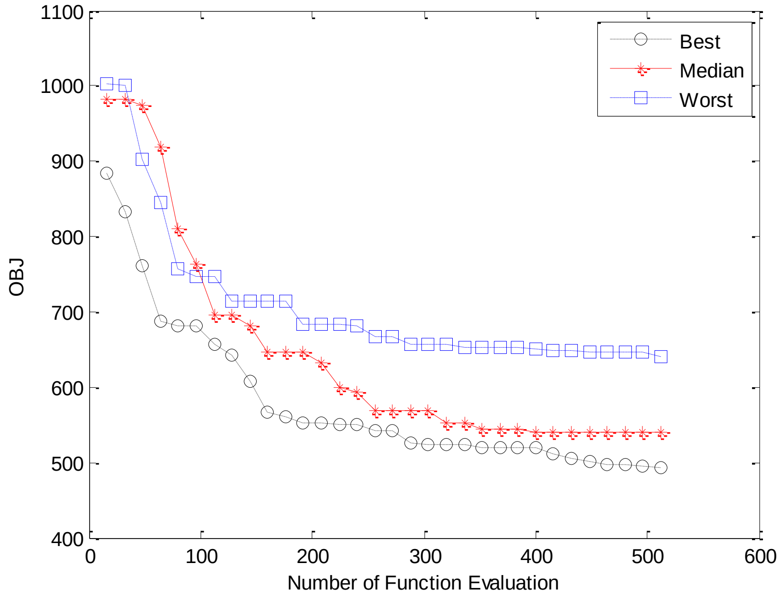

Figure 6.43 Nfevs = 500 total time (8.5″ section)

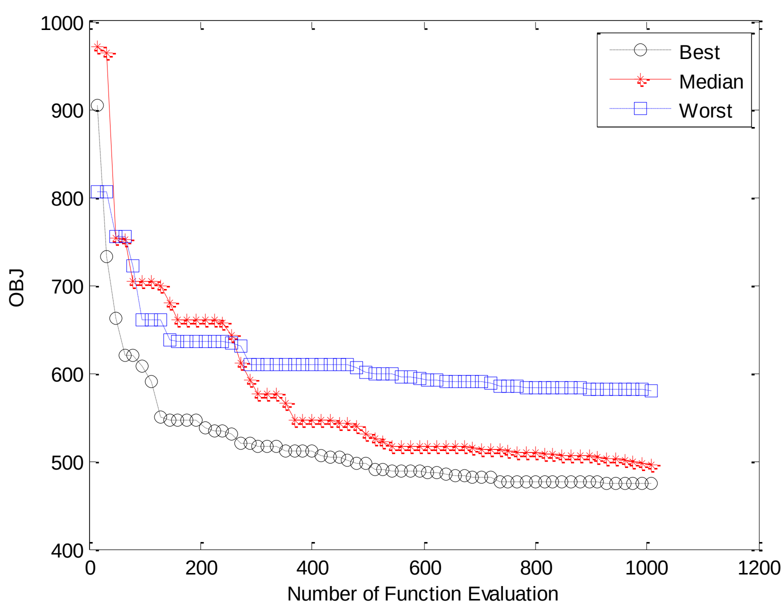

Figure 6.44 Nfevs = 1000 total time (8.5″ section)

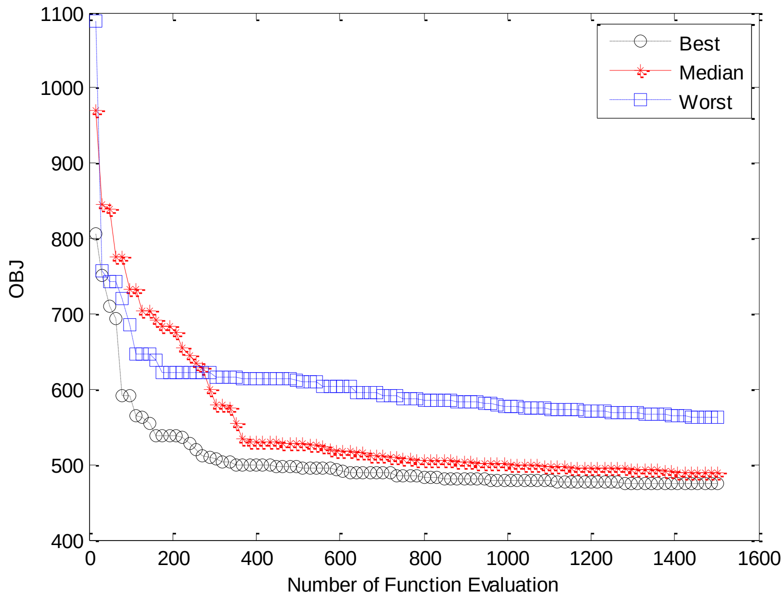

Figure 6.45 Nfevs = 1500 total time (8.5″ section)

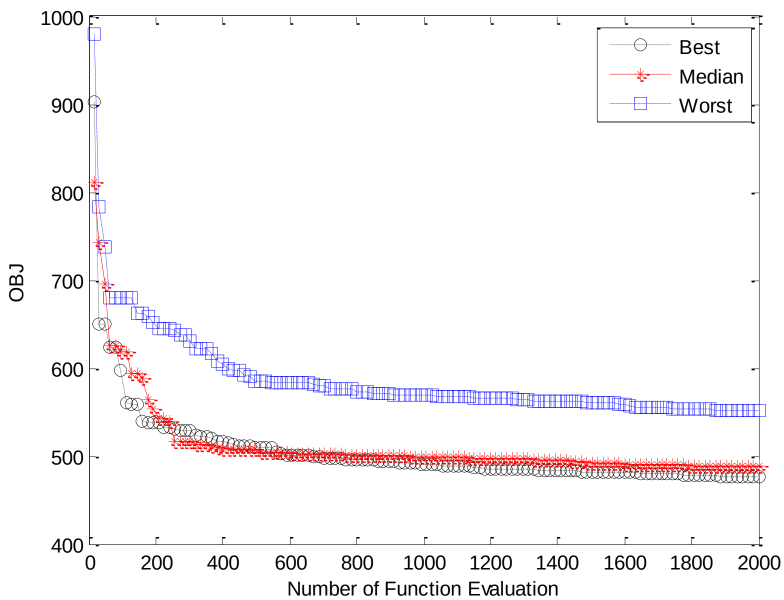

Figure 6.46 Nfevs = 2000 total time (8.5″ section)

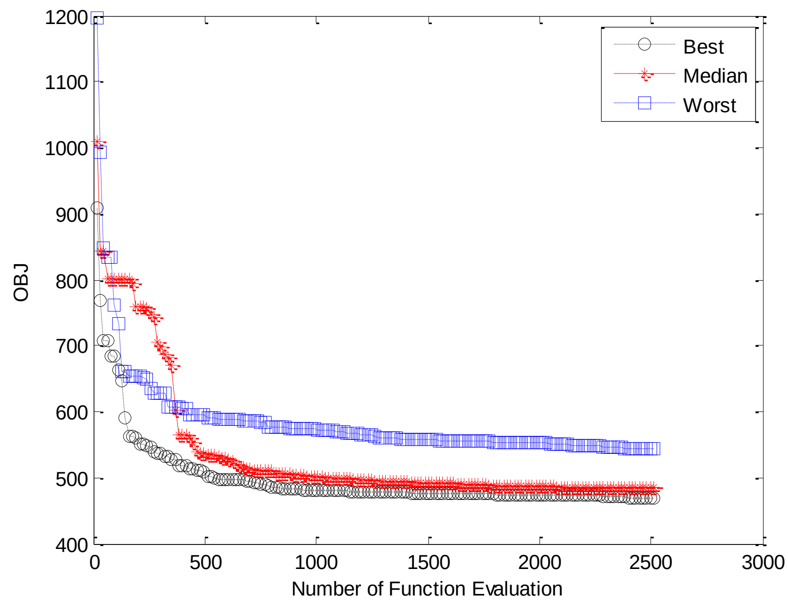

Figure 6.47 Nfevs = 2500 total time (8.5″ section)

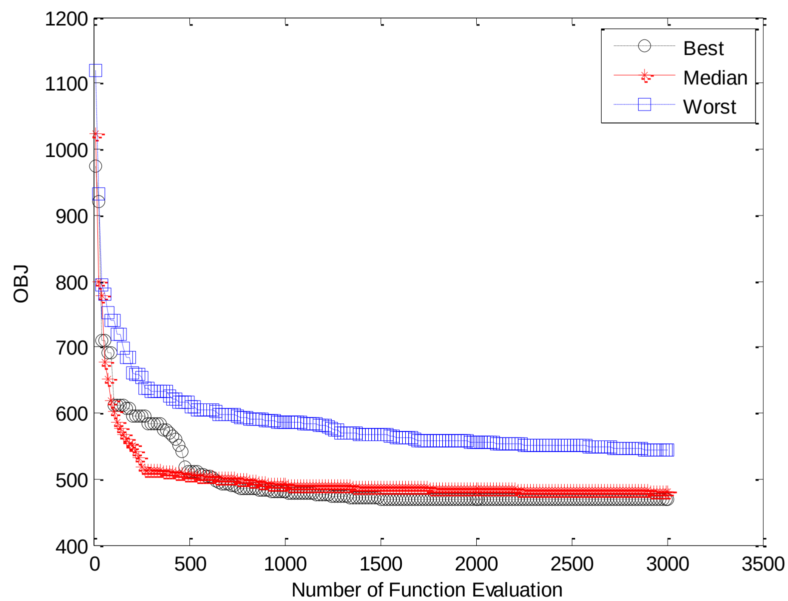

Figure 6.48 Nfevs = 3000 total time (8.5″ section)

From Figure 6.48, it is clear that the best choice for the Nfev is 3000, at which good flattening for the three plots: the best, the median and the worst achieved. Therefore 3000 has been set as the number of function evaluations in the algorithm.

A run was made in order to estimate the parameters that yield the minimum total time required to drill the main section. Figure 6.44 shows the optimized total time and the actual total time recorded during drilling.

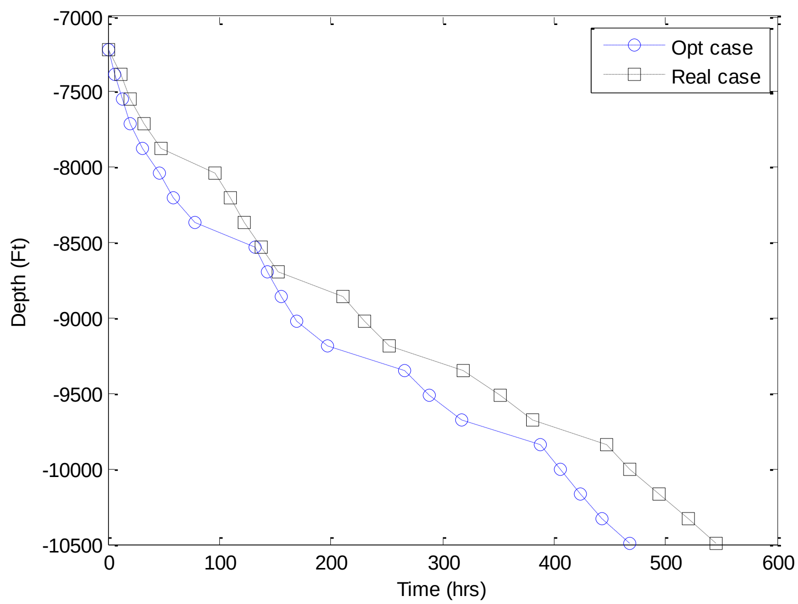

Figure 6.49 Total time of real case and optimized case (8.5″ section)

The total time spent in the actual case was 545 hours - 22.7 days, but the optimization result shows completing the same section in 468 hours – 19.5 days. Hence more than 3 days saving was obtained.

This reduction in time is a result of improving the ROP through the parameters optimization. Figure 7.50 shows the optimized ROP compared to the actual field ROP.

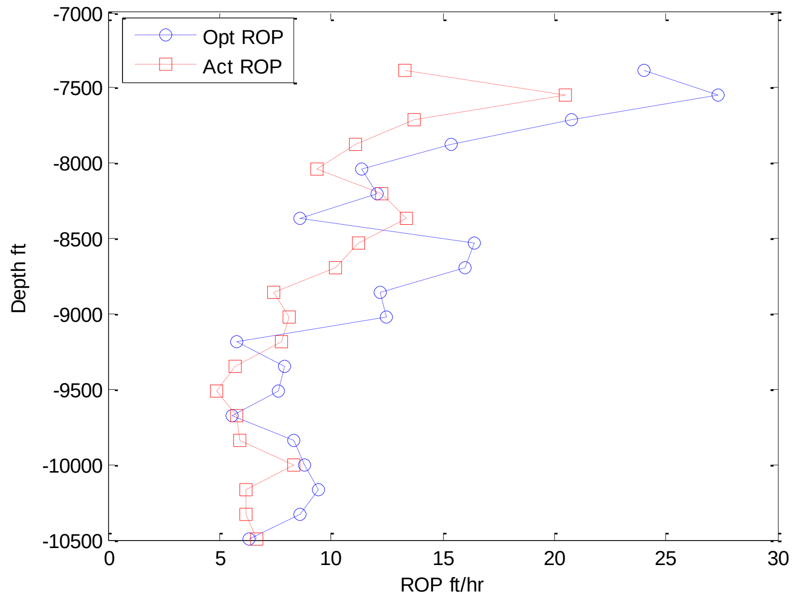

Figure 6.50 Real ROP and optimized ROP – total time (8.5″ section)

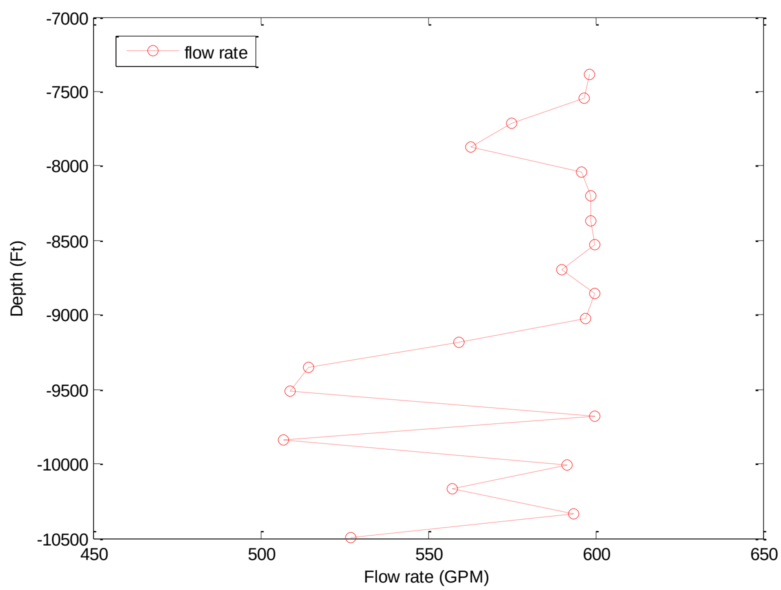

Figure 6.51 Optimized flow rate-total time (8.5″ section)

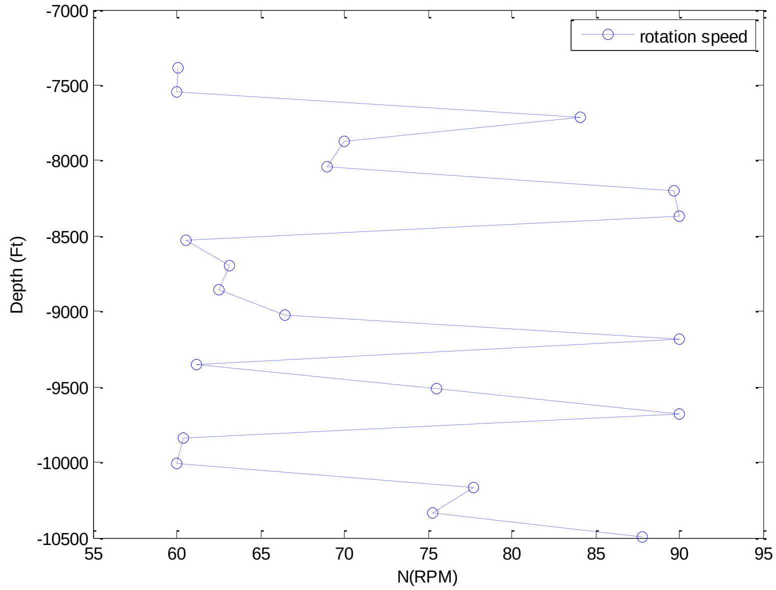

Figure 6.52 Optimized rotation speed– total time (8.5″ section)

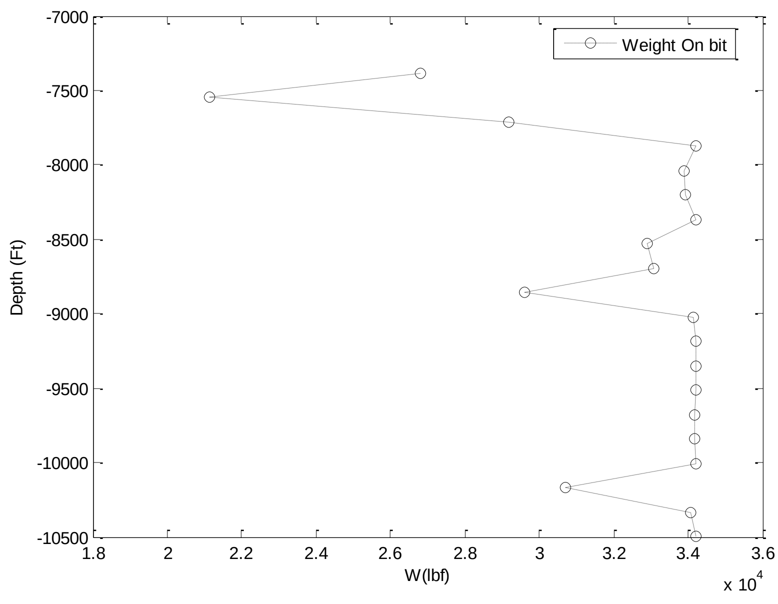

Figure 6.53 Optimized weight on bit-total time (8.5″ section)

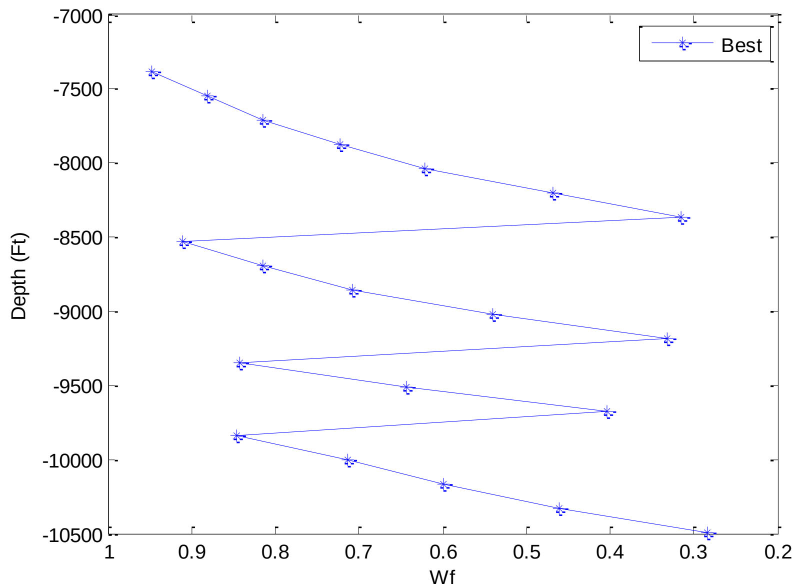

Figure 6.54 Wf vs depth- total time (8.5″ section)

Figures 6.51, 6.52 and 6.53 show the optimized values of flow rate, RPM and WOB respectively. It's clear from Figure 6.54 that 4 bits were used in this section whereas in the actual case 5 bits were run, so the total time and the number of the bits in this section were reduced, hence more than 3 days of rig costs and 1 bit cost were saved.

In the previous section the parameters were optimized to improve the ROP but here the algorithm is set to test the highest values of the parameters in order to see the effect of this on the total time. Figure 6.55 shows the total time for cases of using the optimized parameters and the upper limits values of the parameters from the actual reports.

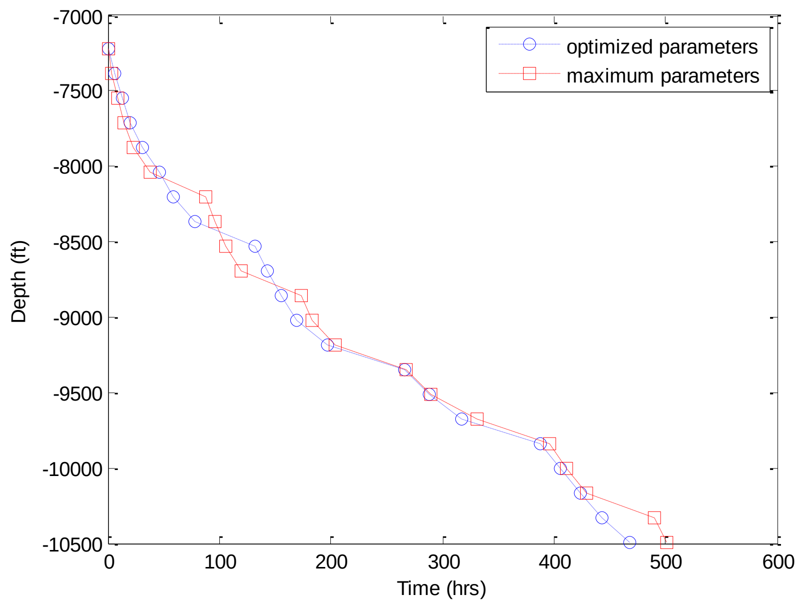

Figure 6.55 Total time - 8.5″ section (6744-34100 lbf)

As it's clear from figure 6.55 applying the optimum parameters lead to a total time of 468 hours- 19.5 days whereas applying the maximum parameters values improve the ROP in some places and consequently requires more trips but eventually it ends up in 501 hrs - 21 days total time.

Therefore, it is clear here that the high ROP doesn't necessarily lead to smaller total time.

B.2: Recommended operational parameters

Here we investigate on the use of higher values of WOB. These values fall within the workspace of manufacturer recommended parameters values, the increment in the WOB values is every 2500 lbf and the difference in time between using the highest values and the optimum values is displayed in the Figures 6.56 to 6.60.

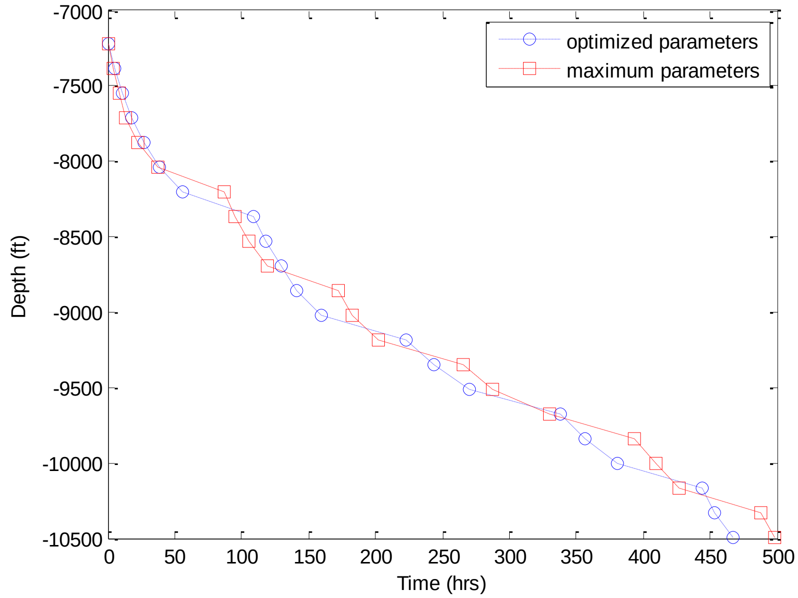

Figure 6.56 Total time - 8.5″ section (6744-35000 lbf)

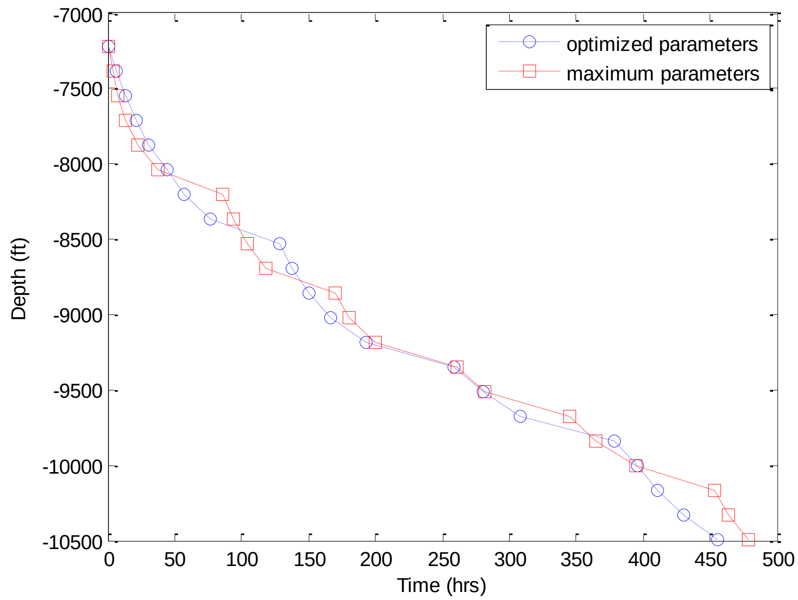

Figure 6.57 Total time - 8.5″ section (6744 - 37500 lbf)

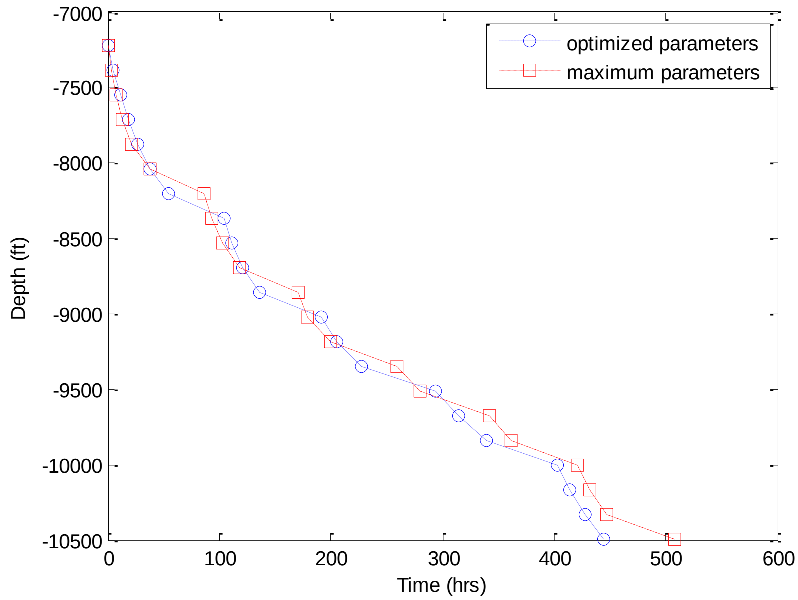

Figure 6.58 Total time-8.5″ section (6744-40000 lbf)

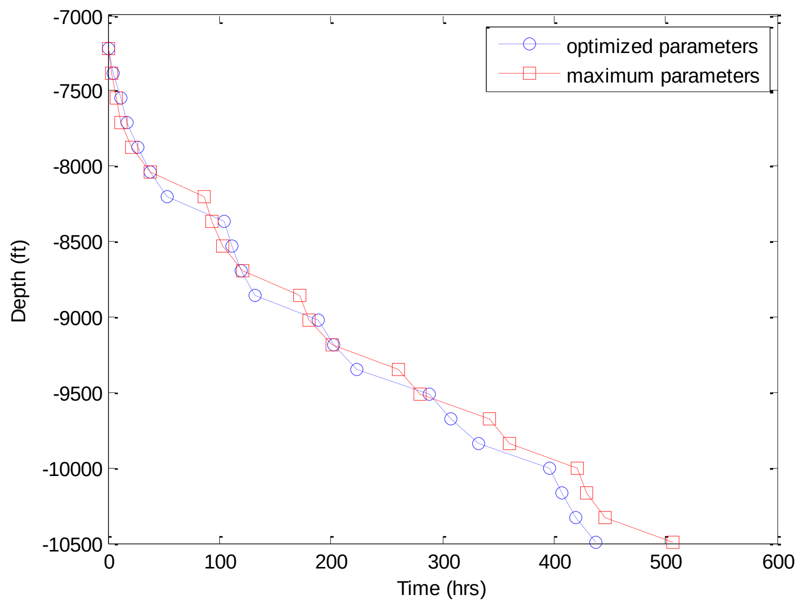

Figure 6.59 Total time - 8.5″ section (6744-42500 lbf)

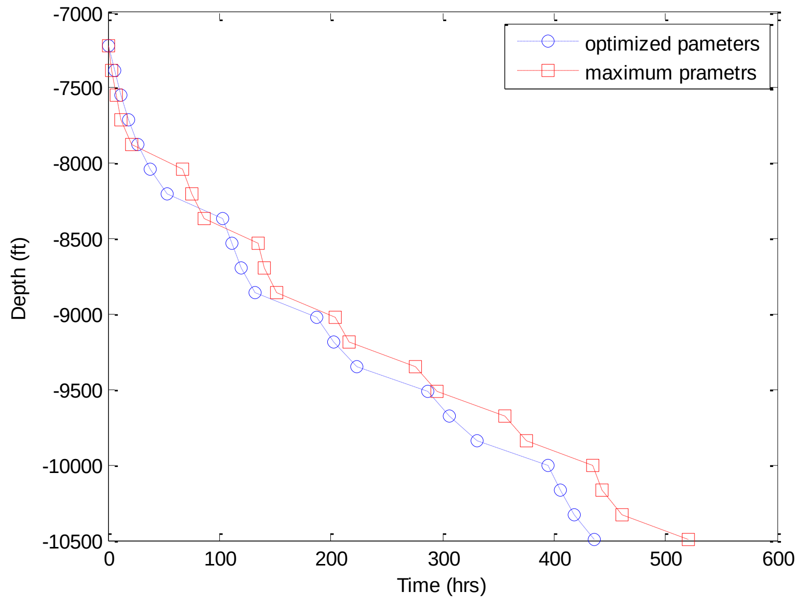

Figure 6.60 Total time - 8.5″ section (6744-45000 lbf)

The increment in the upper limit of the WOB is according to operational recommended parameters sheet. The difference between the optimized total time and the total time obtained from the maximum parameters increases as the WOB increases, In Figures 6.58, 6.59 and 6.60 the optimization shows a difference in total time of 2.6 days, 3days and 3.5 days, respectively between the optimized results and the results obtained from the maximum parameters.

Hence, increasing parameters values, to increase ROP doesn’t always mean getting less total time.

6.3 WOB and Wf Analysis

In this part another type of plots are presented showing the difference in the time between using the maximum parameter values and the optimum parameter values for different values of WOB upper limit and minimum Wf value.

The plots are presented for various WOB ranges by changing the upper limit up to the highest value recommended by manufacturer (Time vs Wf).

The aim of this analysis is to find the best combination of WOB and Wf values that extend the effective bit life and improve the ROP to get the lowest total time.

7.3.1 Intermediate Hole (12.25″)

(Time vs Wf) for different WOB values

In this section we study the effect of changing the minimum Wf value on the time difference between using the optimum parameters values and the highest parameters values in the intermediate section. Many runs were made and the Figures 6.61 to 6.66 show the total time vs Wf for different WOB values are shown.

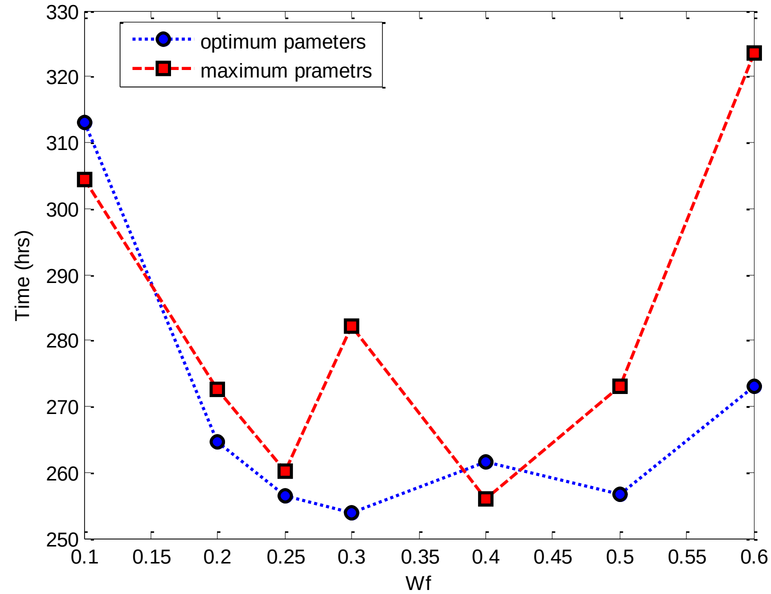

Figure 6.61 Total time vs Wf (WOB ≤ 31400 lbf) – 12.25″ section

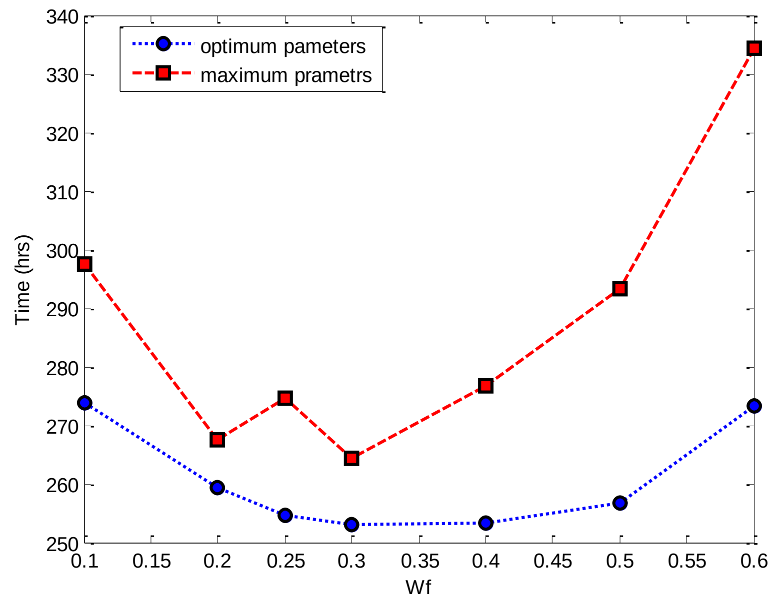

Figure 6.62 Total time vs Wf (WOB ≤ 35000 lbf) – 12.25″ section

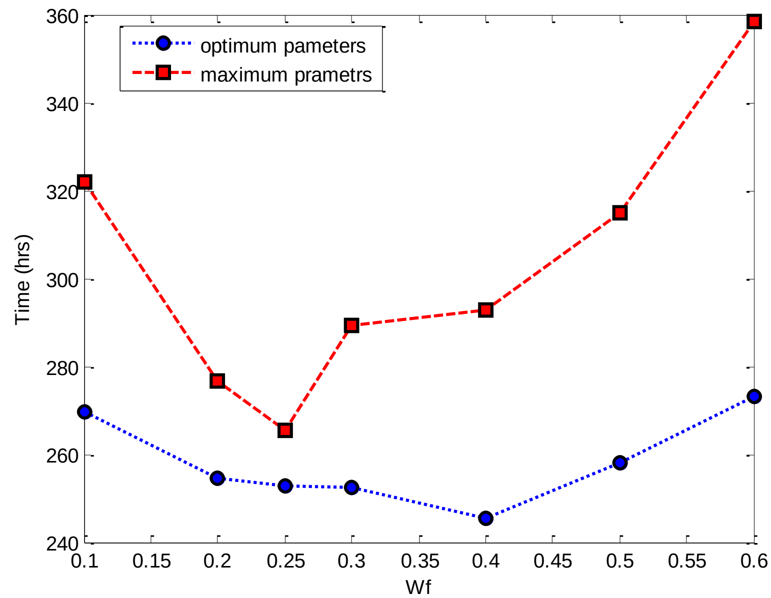

Figure 6.63 Total time vs Wf (WOB ≤ 40000 lbf) – 12.25″ section

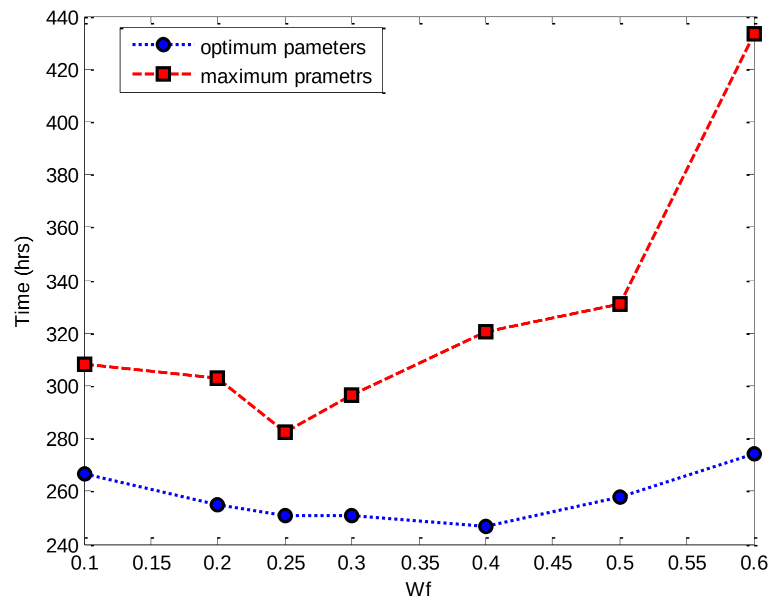

Figure 6.64 Total time vs Wf (WOB ≤ 45000 lbf) – 12.25″ section

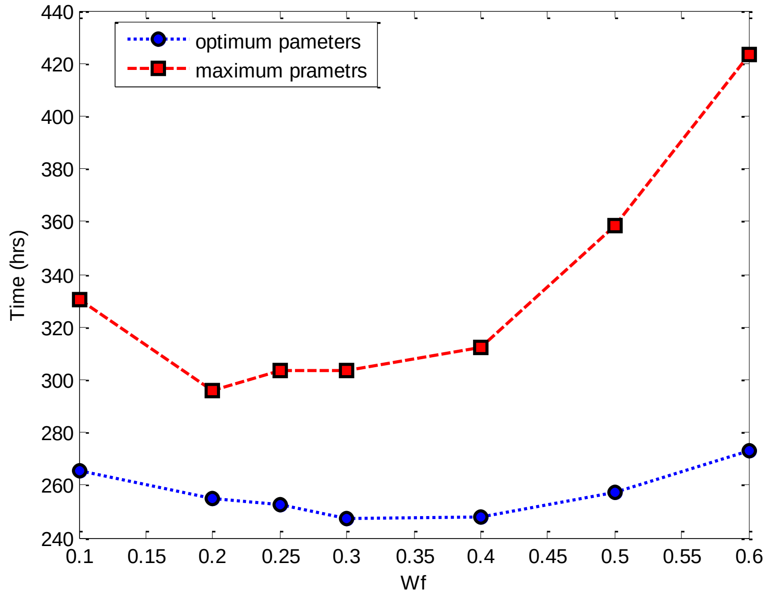

Figure 6.65 Total time vs Wf (WOB ≤ 50000 lbf) – 12.25″ section

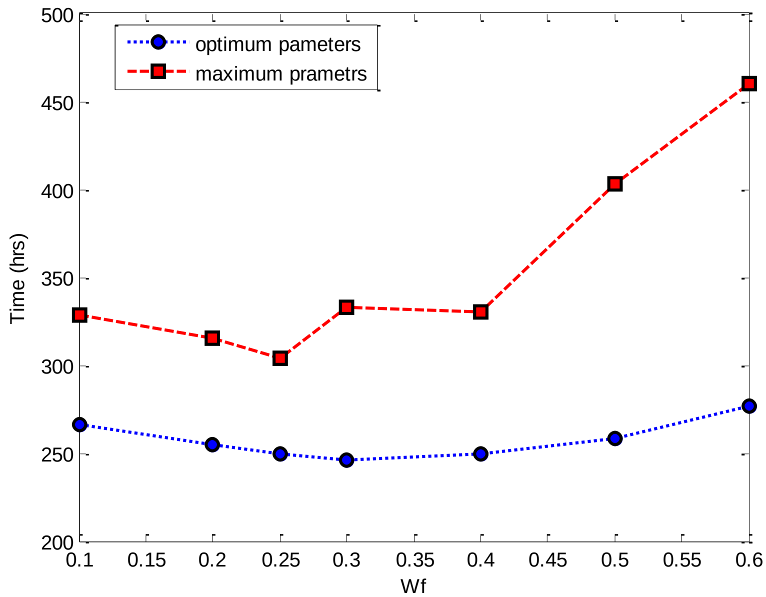

Figure 6.66 Total time vs Wf (WOB ≤ 55000 lbf) – 12.25″ section

Figure 6.61 is a result with WOB upper limit value extracted from the actual reports, the figure shows that pulling the drilling bit at very low values of Wf, which means using the bit for long time until it reaches extreme worn condition, will lead to very low ROP. Hence, more time will be consumed and drilling until these low Wf values are achieved will not beneficial any more. In addition to that, the optimization in this range of low Wf values doesn't add a value because using the maximum values of parameters gives less time than using the optimum parameters values.

The same figure shows pulling the bit at high values of Wf (> 0.5) will require more number of bits and consequently more trips to complete the drilling of the entire section, hence more time will be spent. Since the aim of this work is to reduce the total time, it is recommend in this case to pull the bit out at the range of Wf (0.25-0.35), the optimization has a great contribution in this range because of the total time difference between using the maximum parameter values and the optimum parameter values.

Figure 6.62 shows the total time vs Wf when 35000 lbf used as upper value for the WOB. the optimization shows good results along the x axis where the Wf values start form 0.1 up to 0.6. We observed that pulling the bit at too low or too high values of Wf would lead to larger total time. Therefore, the optimum value of Wf in this case is 0.3, where the lowest total time is achieved, Also the optimization shows a difference of 12 hours saving between using the maximum parameters and the optimum parameters when the bit pulled at Wf=0.3.

Figures 6.64, 6.65 and 6.66 show also considerable differences in time, between using the maximum parameter values and optimum parameter values, so the optimization has a great positive impact.

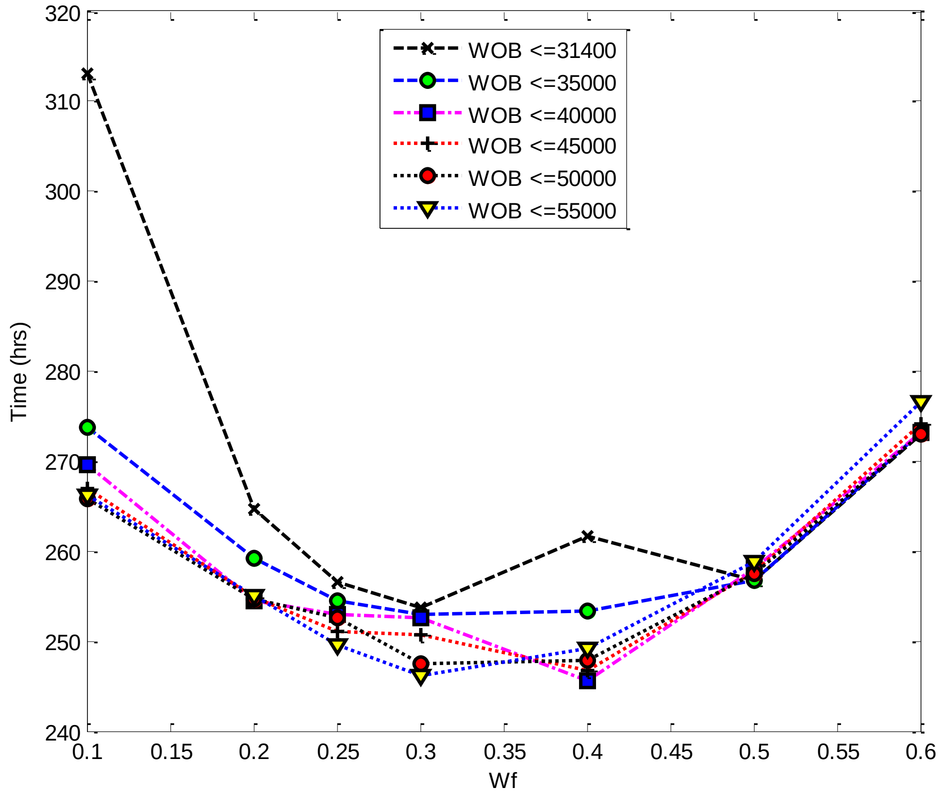

Figure 6.67 Optimized total time for all WOB values – 12.25" section

Figure 6.67 combines all the optimum parameters time curves for the different WOB values. We observe from the figure that all the WOB values yields the lowest time at Wf values of 0.25 to 0.4. Hence these are the optimum range of values for minimum Wf, at which the bit should be pulled and replaced with a new one.

The case of WOB ≤ 31400 lbf (base case) shows the lowest total time of 253 hrs(10.5 days) at Wf=0.3 with usage of 3 bits, whereas the cases of WOB ≤ 40000 lbf and WOB ≤ 55000 lbf show the lowest total time of 245 hrs (10.2 days) at Wf=0.4 and Wf=0.3 respectively, with usage of 4 bits, the little delay in total time in WOB ≤ 31400 lbf case would be less costly than adding new bit to complete the section in WOB ≤ 40000 lbf case , hence it's recommended to use WOB ≤ 31400 lbf and to pull the bit the optimum value of the Wf = 0.3 .

7.3.2 Main hole (8.5″)

(Time vs Wf) for various WOB values

In this section,we study the influence of changing the minimum Wf value and increasing the WOB values according to the operational recommended parameters sheet on the difference in the total time between applying the optimum parameters values and the highest parameters values for the main section.

Figure 6.68 shows the plot of total time (hours) versus Wf.

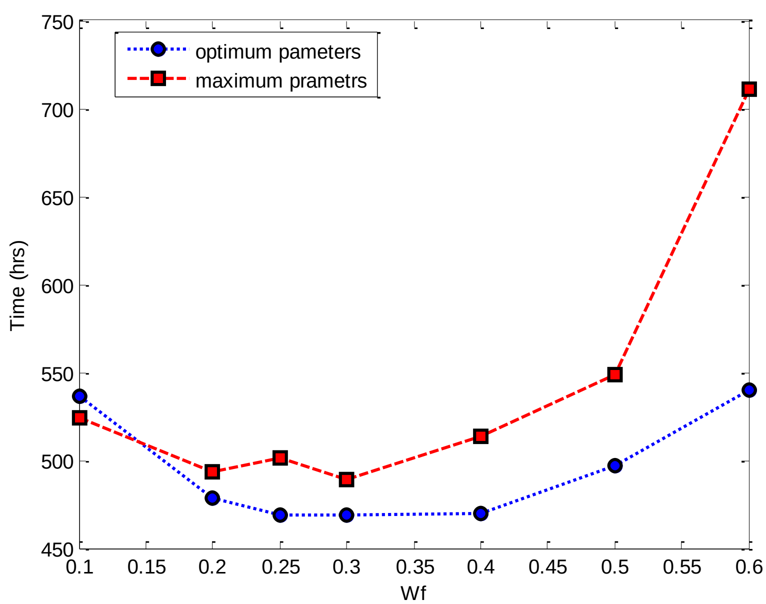

Figure 6.68 Total time vs Wf (WOB ≤ 34100 lbf) – 8.5″ section

It is assumed that applying WOB ≤ 34100 lbf that gives 468 hours (19.5 days) total time at Wf = 0.25 is the base case because this upper WOB value has been applied in the field and shown in the actual reports of this well

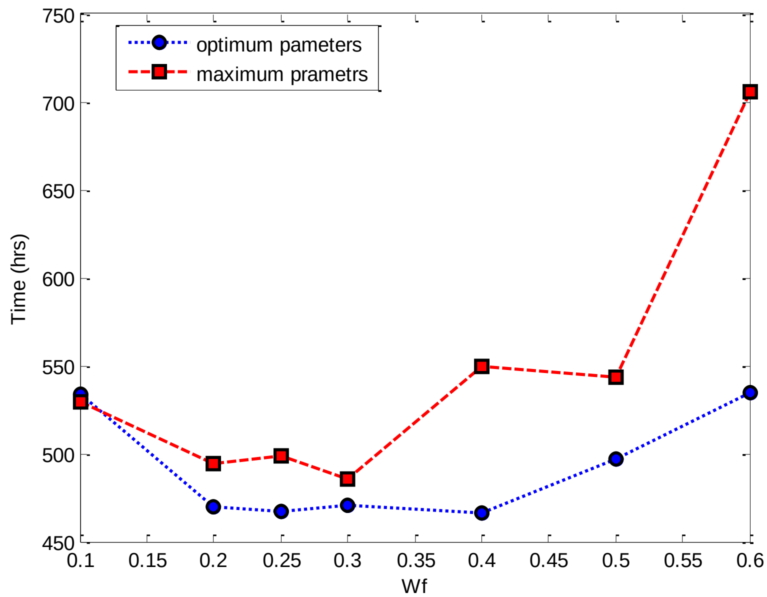

Figure 6.69 Total time vs Wf (WOB ≤ 35000 lbf) – 8.5″ section

It is clear that pulling the drilling bit at very low values of Wf, after it reaches close to the complete worn condition, leads to high total time compared to the base case. In addition to that, the optimization failed to reduce the optimized total time to values below the total time from the maximum parameters, Hence, this low range of Wf values < 0.15 is not recommended to be applied. Also pulling the bits in this case at high values of Wf > 0.4, leads to increase in the total time. Therefore the best range of Wf values at which the bits should be pulled out to give the lowest total time and bits number is the range of [0.2 - 0.3].

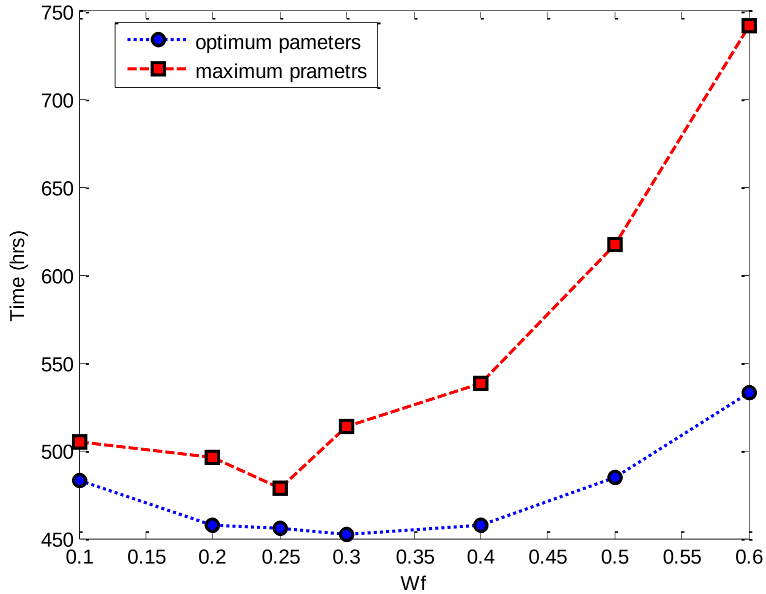

Figure 6.70 Total time vs Wf (WOB ≤ 37500 lbf) – 8.5″ section

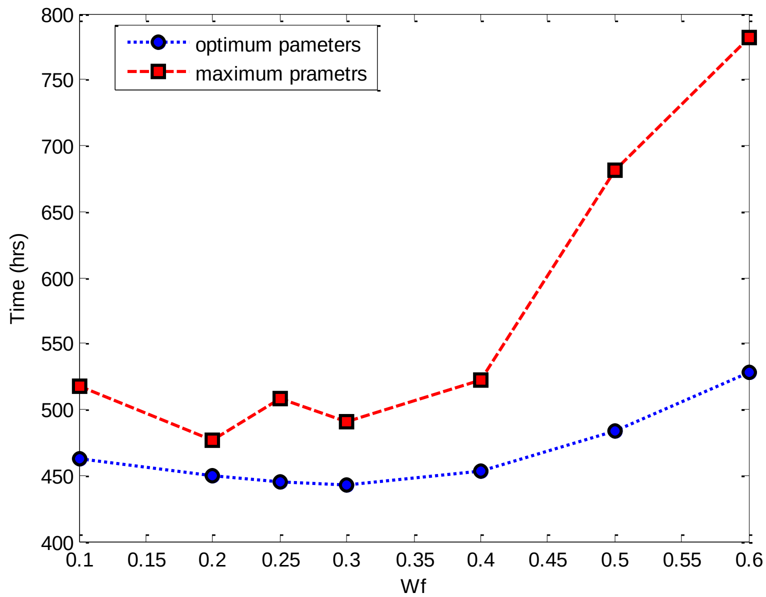

Figure 6.71 Total time vs Wf (WOB ≤ 40000 lbf) – 8.5″ section

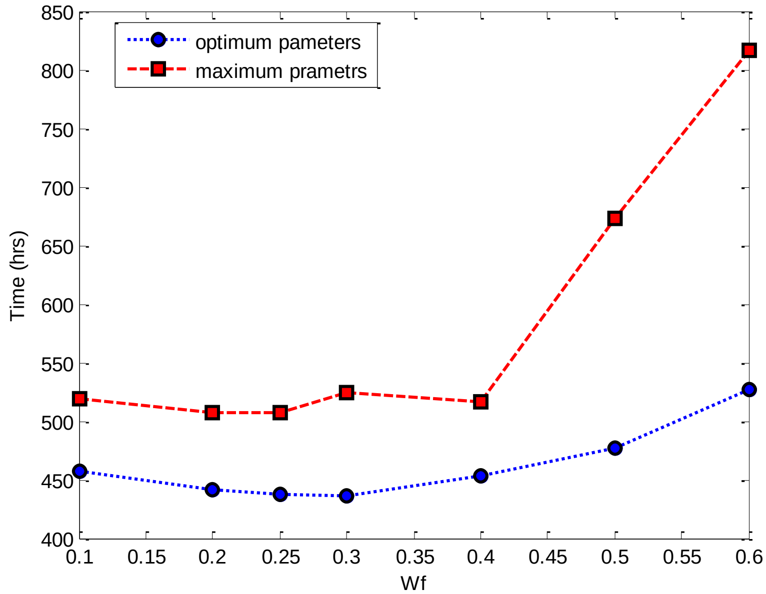

Figure 6.72 Total time vs Wf (WOB ≤ 42500 lbf) – 8.5″ section

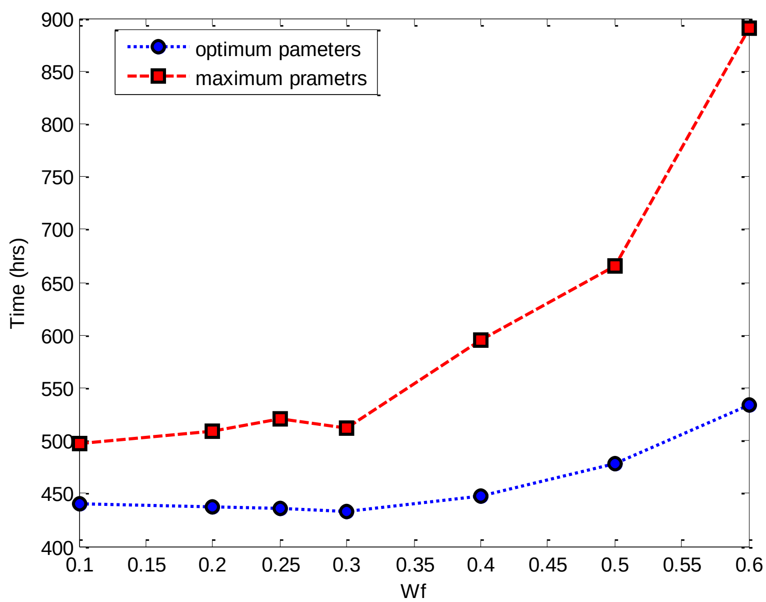

Figure 6.73 Total time vs Wf (WOB ≤ 45000 lbf) – 8.5″ section

The Figures 6.70 – 6.73 exhibit the same general trend and the total time difference increases at some ranges of Wf in the higher WOB values, however the optimized total time for the all cases of WOB values combined in Figure 7.74 followed by discussion.

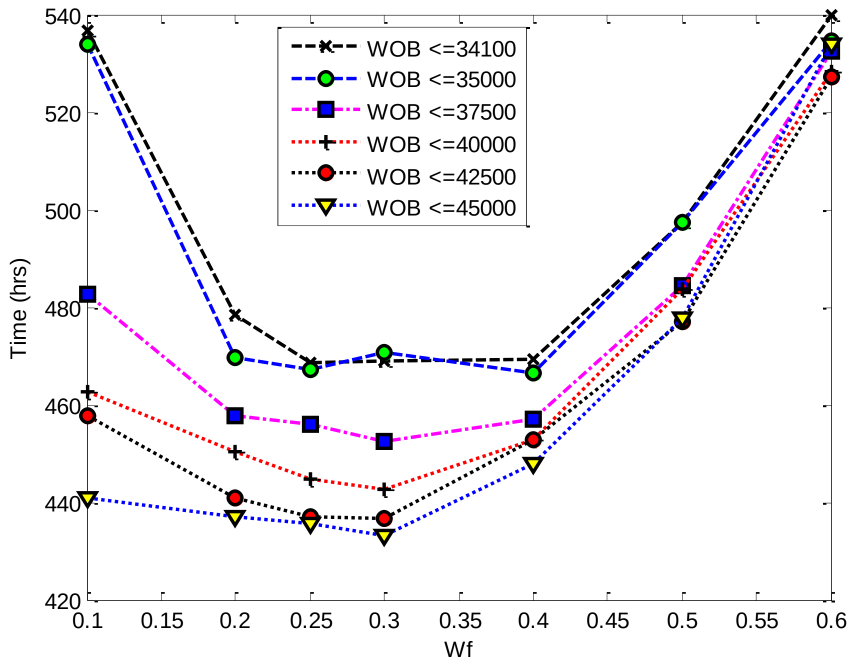

Figure 6.74 Optimized total time for all WOB values – 8.5″ section

Figure 6.74 shows different cases of applying WOB ranges within the ranges of the recommended operational parameters sheet. As it's can be seen from the figure all the cases of WOB show the lowest time at Wf (0.2-0.3). Thus, this is the optimum range of Wf values at which the bit should be pulled.

The figure also shows clearly in the optimum range of Wf values that increasing the WOB has major effect in reducing the optimized total time. In the case of WOB $\leq$ 34100 the lowest total time is 468 hrs (19.5 days) shown at Wf= 0.25,in which 4 bits were used to complete this section. Whereas the WOB values ≤ 42500 and ≤ 45000 give the lowest total time about 430 hrs (18 days) at Wf=0.3, the number of the bits used in this case is 5. Hence, cost analysis is required to decide which one is more cost effective, completing the section with 4 bits and a delay of 1.5 days, or adding new bit cost and saving the 1.5 days. In this field the daily rig cost + service companies daily cost was about 45000 $/day whereas the bit costs about 17000 $. Hence, it is recommended to add 1 more bit to complete the section .

CONCLUSIONS AND RECOMMENDATIONS

Conclusion

1- QA/QC has been performed through combining DDR and MLD to increase the reliability of the parameters and data.

2- Modified Warren Model showed good compliance with AG formation in this field.

3- Differential Evolution was successfully used as a global optimization technique yields recommended parameters values that lead to reduce the drilling time and the total time in the drilling operations.

4- The results of the drilling time optimization in 12.25″ section shows completing the section in 8.3 days , whereas the actual case took about 10.5 days, so the optimization shows more than 2 days saving in the rig time which is 21% of actual drilling time. In the 8.5″ section the drilling consumed about 16.67 days drilling time, while the optimized parameters yields 13.3 days drilling time. Thus 3.3 days saving was achieved. This represents a reduction of 20% of the actual drilling time, hence the total cost saving in the intermediate and the main hole sections is the daily rig cost multiplied by 5.3 days .

5- For the total time, the optimization results shows that the intermediate section, takes 10.4 days, whereas the time spent in the actual case was 14.5 days, so we have about 4 days saving ahead of the actual total time and this reduction in time is approximately 27.5 % from the actual case, In the main hole, the actual case took 22.7 days total time, while the optimized case shows 19.5 days total time. Thus, more than 3 days of rig cost saving was obtained. The total saving in the intermediate and main hole is 7 days of rig cost.

6- In the actual case for the intermediate section 4 bits were run, while the optimized case shows usage of 3 bits. Also 5 bits were run in the main hole in the actual case whereas the optimized case shows 4 bits. Hence saving of two bits cost is obtained from optimization process.

7- This algorithm can be applied in real time drilling operations to optimize the bit life, thus providing insight on the optimum time or depth at which the bit should be pulled to achieve the lowest total time.

8- It has been shown through this study that increasing the ROP doesn't always means achieving lower total time. The difference in total time between using the maximum parameters and optimum parameters with filed constraints (parameters ranges) is low in the intermediate section, because of its shallow TD whereas this difference reaches about 1.5 day in main section. Hence, this optimization technique has great positive and considerable effects in the deeper sections.

9- WOB and Wf analysis has been performed and from this analysis it has been shown that the best range of Wf at which the drilling bits should be pulled out is [0.25-0.4] in the intermediate section (shallow), and [0.2-0.3] in the main (deeper) section

10- In the main section, the base case (applied in the field) uses WOB ≤ 34100, increasing the WOB to ≤ 42500 gives about 1.5 days reduction in the total time, but requires adding 1 bit, the cost of adding new bit is less than the daily rate of the rig and service companies, hence it's recommended to apply WOB ≤ 42500 .

Recommendations

1- Conducting rock mechanical tests on core samples from the field to ensure the accuracy of rock strength data.

2- Applying this work on the deep wells.

3- Applying this work on PDC models.

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