Analysis and Multi-Objective Optimization of the Rate of Penetration and Mechanical Specific Energy: A Case Study Applied to a Carbonate Hard Rock Reservoir Based on a Drill Rate Test Using Play-Back Methodology

Diunay Zuliani Mantegazini 1, Andreas Nascimento 1,2, Vitória Felício Dornelas 1,* and Mauro Hugo Mathias 1

1 Graduate Program in Engineering, São Paulo State University, Guaratinguetá 12516-410, SP, Brazil; diunay.mantegazini@unesp.br (D.Z.M.); andreas.nascimento@unifei.edu.br (A.N.); mauro.h.mathias@unesp.br (M.H.M.)
2 Institute of Mechanical Engineering, Federal University of Itajubá, Itajubá 37500-903, MG, Brazil
* Correspondence: vf.dornelas@unesp.br

Abstract: Until early 2006, in Brazil, the focus used to be on oil and gas exploration/exploitation of post-salt carbonates. This changed when the industry announced the existence of large fields in pre-salt layers across the South Atlantic Ocean from nearshore zones up to almost 350 [km] from the shore. With the discovery of pre-salt hydrocarbons reservoirs, new challenges appeared. One of the main challenges is the necessity to optimize the drilling processes due to their high operational costs. Drilling costs are considerably high, which leads the oil and gas industry to search for innovative and entrepreneurial methods. The coupling of the mechanical specific energy (MSE) and the rate of penetration (ROP) is a method that allows for the identification of ideal conditions to efficiently enhance the drilling process. In addition, the performance of the drilling process can be estimated through pre-operational tests, which consist in continuously testing the applied drilling mechanic parameters, such as the weight-on-bit (WOB) and drill string rotary speed (RPM), looking for optimum sets that would ultimately provide the most desirable ROP. Thus, the goal of this research was to analyze field data from pre-salt layer operations, using a multi-objective optimization based on the play-back methodology for pre-operational drilling tests, through the ideal combination of the highest ROP and the lowest MSE. The results showed that the new concept of pre-operational tests based on the MSE proved to be effective in the drilling process optimization. The combination of the highest ROP and the lowest MSE allows for a high-performance drilling process. For WOB intervals of 5 and 7 [kib], a good fit of the parameters was obtained. Through the parameters obtained from pre-operational tests, the eventual cost-saving and time-saving values could be estimated, respectively, ranging from USD 1,056,180 to 1,151,898 and 19.50 to 21.27 [h], respectively. In addition, the results of this research can be applied to the exploration of other natural resources, such as natural hydrogen and geothermal sources.

Keywords: desirability; drilling; pre-salt layers; carbonate hard rock; pre-operational test; oil and gas

1. Introduction

The oil and gas industry is still one of the biggest economy drivers in the world [1]. The discovery, exploration, and exploitation of hydrocarbons (HC) from pre-salt carbonate hard rocks are key steps forward in this sector [2]. The pre-salt region in Brazil is recognized as the biggest set of recently discovered giant oil fields in the world [3]. However, more than ten years after its discovery, operations in the pre-salt carbonates continue to present challenges in terms of drilling, production, and also in relation to the reservoir characterization [4,5]. Pre-salt carbonate reservoirs are highly complex and heterogeneous [2,6,7], a feature justified by the nature of the original deposition system and the subsequent diageneric processes [2].
Optimizing the drilling processes and reducing the costs of production are extremely important to maximize profitability in the oil and gas industry [8]. Due to the ongoing considerable demand for hydrocarbons on a global scale, the oil and gas industry has always tried to find novel solutions, especially for drilling operations, to diminish the operational costs [9–11]. Drilling operations are very expensive, challenging, and involve risks and different problems, especially with deep drilling and activities through hard formations [12–15]. Due to these facts, the drilling process has gained notable technological improvements in recent years [16]. For example, current bottom hole assemblies have several sensors, which allow for the monitoring, steering, and optimization of the drilling process by measuring the geological and directional information of the borehole while drilling [17].

Industries within the sector are motivated to implement technologies that focus on cost and operational optimization [18,19] and solve the challenges still found in petroleum exploration [20]. The rate of penetration (ROP) is one of the main parameters affecting the process of oil and gas well drilling optimization and the total drilling costs [1,21–24]. The ROP can be defined as the speed at which a drill bit breaks through a formation, deepening (advancing) the borehole [25], or as the volume of rock removed per unit area per unit time [22]. An ROP prediction can help in planning the drilling process and reducing the drilling costs [14,26]. Finding an accurate method for ROP prediction has been one of the objectives of the oil and gas industry since the 1950s [27]. Due to the complex relationship between the parameters affecting the ROP, an accurate prediction of the ROP is very difficult to obtain [22,28]. There are many drilling variables that affect the ROP, such as the weight-on-bit (WOB), drill string rotation speed (RPM), torque-on-bit (TOB), standpipe pressure (SPP), flow rate (FLOW), as well as the depth and lithology [27,29,30].

Increasing the ROP has been the main target of drilling in the O–G industry [31]. Excessive increases in the ROP can cause problems such as stuck pipes, poor hole cleaning, and drill bit tooth wear [26] in addition to drilling vibrations and fast drill bit warming [32,33]. Therefore, there is an ideal (or optimized) value for the ROP for each situation and scenario, where decreases in the operation time and drilling costs are more likely to be achieved [34]. The mechanical specific energy (MSE) and ROP are two key factors for evaluating the efficiency of a drilling process [35]. The combination of both factors allows for the optimization of the drilling process [20]. The MSE has been utilized as a tool for evaluating the performance of the drilling process, where the maximum efficiency can be reached at the point where the MSE has the lowest value [36].

The MSE has been widely used to quantify the efficiency of the drilling process [37]. The concept of MSE was first introduced by Teale in 1965 [38]. The MSE is defined as the energy required to remove a unit volume of rock [23,35–37,39]. The MSE has also been applied to formation lithology prediction [14,39]. Due to the difference in rock strengths, when sudden lithology changes occur, the MSE values may also significantly change [40]; these are linked to other parameters such as the drilling speed (or ROP) [39]. The MSE must be numerically close to the ultimate confined compressive strength (UCCS) of the formation; in other words, the lowest value of MSE corresponds to the UCCS [36,37].

The performance of the drilling process can be estimated through a pre-operational test, which is a simple and practical procedure to determine the relation between the ROP and the parameters WOB and RPM [41]. The test consists in continuously increasing the WOB while keeping the RPM fixed at a short depth interval to obtain the ROP values, which is repeated for different RPMs [42]. It has a new focus in the oil and gas industry to relate the drilling performance to the MSE obtained during the drilling operations. The achievement of the highest ROP, as it has been applied in the industry, may not be applicable anymore. In this sense, a new concept of pre-operational tests based on the MSE was presented by [43], comparing the interpreted relation of the WOB vs. ROP with the WOB vs. MSE for different RPMs.

Another important aspect is the use of these technologies in the exploration of other natural resources. Nowadays, the exploration of petroleum, natural gas, and geother-
mal sources is gaining importance due to the increase in the demand for these energy sources [16]. The advantages of using geothermal energy to produce heat and/or power include the large number of geothermal resources available, low operating costs, and the expected contribution to the decarbonization of the energy sector [44]. Drilling costs can account for more than 60% of the total cost of an enhanced geothermal system (EGS) [45].

Most of the research performed on the topic proposes a single-objective optimization approach. Thus, this research aims to analyze the field data from pre-salt operations, using a multi-objective optimization based on the recreation of pre-operational drilling tests. The multi-objective optimization of the drilling process will be performed using the ideal combination of the highest ROP and the lowest MSE, allowing for the discovery of the best set of drilling mechanics parameters for the specific lithology studied.

2. Theory of Pre-Operational Testing

One of the main problems during the drilling process is the excess of hardness and abrasiveness found in pre-salt carbonates. These characteristics can lead to early drill bit teeth-cutter breakage/dullness/wear [43]. All these events affect the drilling efficiency in pre-salt operations. The drilling efficiency is directly proportional to the total non-productive time (NPT) [46]. Usually, the NPT represents one-third of the total rig operational expenditure [47]. A statistical analysis in the Gulf of Mexico showed that in 10 years, more than 12% of the NPT was due to a loss of circulation and about 18% was a result of kicks and wellbore instabilities [48]. A similar analysis showed that lost circulation can increase drilling costs by USD 70 to 100 per foot [49]. In this context, there is still room for improvements in the solutions based on computational tools and more automated activities, which may be applicable not just to pre-salt fields but also to the industry overall, from a global perspective, and for the exploration/exploitation of other natural resources [43].

Thus, considering the actual global scenario of the O–G industry, there is a need to search for ways to increase the efficiency through the development, implementation, and deployment of novel and innovative processes and products [43]. To overcome these obstacles, a methodology to achieve the ideal drilling parameters has to be proposed. The selection of the ideal drilling parameters can lead to the most desirable ROP, allowing for a reduction in the energy consumption and NPT.

The drillability of the formations can be estimated through pre-operational tests, such as the drill rate test (DRT) and drill-off test (DOT). The DRT and DOT methodology were developed in the 1950s to reduce the drilling time by determining the ideal parameters (WOB and RPM) for drilling a specific formation. In addition, the methodology allows for simulations and tendency estimations, enabling a better understanding of the possible parameters and design combinations for operation optimization and efficiency enhancement [50]. Through the DRT, the following questions can be addressed: (a) how large of an increase in the WOB value would be effective and efficient? (b) how much of an increase would lead to unnecessary machinery overload?

The WOB and RPM are critical parameters that must be monitored and optimized in real-time during the drilling process [46]. Other parameters such as the torque, standpipe pressure (SPP), mud weight, and mud rheological properties also play a critical role in achieving a better ROP. However, these parameters cannot be manipulated in real-time, since they are a function of the formation type, lithology, and temperature, among others [51].

The pre-operational test is realized at the beginning of a new phase of the drilling process or formation at a short depth interval, and consists in continuously increasing the WOB, maintaining approximately fixed RPM values (which always vary for another test run with a specific given, fixed RPM) [42]. It is basically a step-by-step process of varying the drilling parameters to maximize the ROP and determine the “founder point”, also known as the “foundering point”. The founder point is defined as the point at which the
ROP stops responding positively to an increase in the WOB and/or RPM [46]. The ROP versus WOB graph is shown for the values obtained in Figure 1.

![Drill rate test curve](image)

**Figure 1.** Drill rate test curve.

The curve has three well-defined regions:

- **Region I:** When starting the drilling process, it is necessary to increase the WOB value, i.e., there is only drill bit penetration after a determined WOB value. This way, an increase in the ROP is the result of a disproportionate increase in the WOB;
- **Region II:** This is defined by a constant slope line with the highest possible efficiency, where an increase in the WOB results in a proportional increase in the ROP;
- **Region III:** This is defined as the region in which the ROP stops responding linearly with an increase in the WOB. In this region, the inflection point is found, i.e., the maximum ROP value for determining the combination between the WOB and RPM. Region IV starts from the inflection point;
- **Region IV:** This region is characterized by processes that restrict the energy transfer, cause vibrations, and reduce the process efficiency. “Bit balling” and “bottom hole balling” are terms commonly used to describe the accumulation of gravel on the drill bit and bottom hole that inhibits the transfer of a part of the WOB to the cutting structure of the drill bit [52]. Downhole vibrations can be divided into three distinct behaviors: whirl (lateral), stick–slip (torsional), and bit bounce (axial). These cause drill bit and downhole tool failures, consequently increasing the cost and time of the drilling process.

It is important to emphasize that the optimization of the drilling process does not simply consist in obtaining the parameters that provide the highest ROP. One must search for parameters that allow for drilling in a faster way. The drill rate test curve used together with the concept of the MSE enables it to obtain parameters that help with the optimization of the drilling process, not only by maximizing the ROP, but looking for the combination between the highest ROP and the lowest MSE through the ideal operating conditions (WOB and RPM). Figure 2 shows the flowchart of the drilling performance prediction and optimization method.

The maximum efficiency in the drilling process is obtained in region III. By increasing the WOB and RPM values, the ROP will decrease and approach region I, characterized by a high MSE value and low ROP value [53].
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3. Materials and Methods

3.1. Data Acquisition

A field dataset from a real pre-salt operation was used in this analysis. The dataset represents a carbonate hard rock reservoir (pre-salt) interval drilled in the South Atlantic Ocean, and contains values of several parameters such as the depth, rate of penetration (ROP), drill string rotational speed (RPM), weight-on-bit (WOB), torque-on-bit (TOB), downhole annulus pressure (DHAP), downhole annulus temperature (DHAT), equivalent circulating density (ECD), standpipe pressure (SPP), and flow rate (FLOW), among others. The analysis was performed considering a measured depth (MD) interval from 17,069.50 to 17,344.50 [ft], which was drilled using a polycrystalline diamond compact (PDC) drill bit with a diameter of 12.25″.

3.2. Mechanical Specific Energy

The MSE value was obtained through the equation presented by Teale (Equation (1)). In 1965, Teale first proposed the equation for calculating the MSE, taking into account the influence of different drilling variables, such as the WOB, RPM, TOB, and ROP, linking all by means of the working efficiency of the drill bit [54].

\[
\text{MSE} = \frac{\text{WOB}}{A_b} + \frac{120\pi \cdot \text{RPM} \cdot \text{TOB}}{A_b \cdot \text{ROP}}
\]

Here, \(A_b\) is the drill bit cross-section area \([\text{in}^2]\), RPM is the drill string rotational speed \([\text{rev/min}]\), WOB is the weight-on-bit \([\text{lb}]\), TOB is the torque-on-bit \([\text{ft-lb}]\), and ROP is the rate of penetration \([\text{ft/h}]\).

3.3. Drill Rate Test

The drill rate test (DRT) is one of the main methodologies used in the O–G industry to calculate the optimal drilling parameters. The steps for the construction of drill rate test curves from a drilling dataset are as follows: (i) The dataset was initially separated by different RPM values using an interval of 10 rev/min. Usually, the petroleum wells are drilled using an RPM from 60 to 160 [rev/min], depending on the specificities of the drilling operations and the provided drilling programs; (ii) For each RPM interval, the mean values of the WOB, ROP, and MSE parameters were determined with respect to the WOB for intervals of 3, 5, and 7 [klb]; (iii) Second-degree polynomial curves for the ROP vs. WOB and MSE vs. WOB were plotted for different RPM intervals.
The analysis considering WOB intervals of 3, 5, and 7 [k lb] was conducted with the goal of determining the smallest number of tests for a given RPM that would allow us to obtain a consistent drill rate in a fast and agile way due to the high daily cost of the drilling rig.

It is known that these tests are neglected due to the false non-advantage impression, because they demand a substantial amount of time to perform. This may give the wrong impression when comparing the operational time gained with the time spent to safely and accurately perform such a pre-operational drilling test.

### 3.4. Desirability Method

Most of the research performed on the topic proposes a single-objective optimization approach. However, some recent works have been proposing a multi-objective optimization approach for determining the drilling mechanics parameters [55,56], accounting for the optimum ROP and MSE concomitantly. A multi-objective analysis may be applicable when several drilling performance indicators are analyzed simultaneously.

One of the most used methods for addressing multi-objective approaches is known as the total desirability (D), which basically transforms the equations that model each of the answers into individual functions and then proceeds to optimize a global function [57]. This method consists of three stages: (1) data collection, (2) model building, and (3) optimization [58].

Derringer and Suich (1980) proposed individual desirability functions based on three response types as follows: nominal-the-best (NTB), larger-the-best (LTB), and smaller-the-best (STB) answers [59].

- **Nominal-the-best (NTB):** The value of the estimated response \( \hat{y}(x) \) is expected to achieve a particular target value \( T \). The NTB response is defined as per Equation (2).

\[
\begin{align*}
    d &= \begin{cases} 
        \left[ \frac{\hat{y} - L}{T - L} \right]^R & \text{if } L \leq \hat{y} \leq T \\
        \left[ \frac{\hat{y} - U}{U - T} \right]^R & \text{if } T \leq \hat{y} \leq U \\
        0 & \text{if } \hat{y} < L \text{ or } \hat{y} > U 
    \end{cases} 
\end{align*}
\]

(2)

- **Larger-the-best (LTB):** The target value \( T \) must reach the maximum value of the function. For this response type, the individual desirability function is defined as per Equation (3).

\[
\begin{align*}
    d &= \begin{cases} 
        0 & \hat{y} < L \\
        \left[ \frac{\hat{y} - L}{T - L} \right]^R & \text{if } L \leq \hat{y} \leq U \\
        1 & \hat{y} > U 
    \end{cases} 
\end{align*}
\]

(3)

- **Smaller-the-best (STB):** The target value \( T \) must reach the minimum value of the function. For this response type, the individual desirability function is defined as per Equation (4).

\[
\begin{align*}
    d &= \begin{cases} 
        0 & \hat{y} < U \\
        \left[ \frac{\hat{y} - U}{T - U} \right]^R & \text{if } L \leq \hat{y} \leq U \\
        1 & \hat{y} < L 
    \end{cases} 
\end{align*}
\]

(4)

In the sequence, the optimization of the responses can be performed using the global function, as represented by Equation (5).

\[
D = (d_1 \cdot d_2 \cdot d_3 \cdots d_n)^{\frac{1}{p}} 
\]

(5)

Here, \( R \) and \( S \) are the weighting factors, \( p \) is the number of responses to be optimized, \( T \) is the target value, \( L \) is the lower limit, and \( U \) is the upper limit.
4. Results

4.1. 2D Analysis

The traditional method of analysis consists in representing the drilling mechanics parameter data through 2D plots as a function of depth. Figure 3 shows the input variables (WOB and RPM) and the response variables (ROP and MSE) of the drilling process analyzed in this research and presented article.

As shown in Figure 3, the mean value of the WOB is 18.27 [klb], varying from 1.09 up to 43.31 [klb]. The RPM’s mean value is 137.99 [rev/min], with a range that varies between 109.36 (minimum value) and 151.77 [rev/min] (maximum value). The mean value of the ROP is 13.00 [ft/h], with a minimum value of 1.29 and a maximum value of 32.12 [ft/h]. The MSE’s mean value is 462.01 [kpsi], with a range that varies between 610.00 [psi] (minimum value) and 3750.44 [kpsi] (maximum value). Moreover, Figure 3 can be divided into two zones. Zone 1, from 17,069.50 to 17,245.50 [ft], is characterized by an efficient process and zone 2, from 17,069.51 to 17,344.50 [ft], is characterized by an inefficient process due to the high value of the WOB, i.e., the drilling process probably occurs in region IV as per Figure 1.

Zone 1 of Figure 3 shows a stable trend, indicating that the MSE, at this time, is relatively low, while the ROP reaches considerably high values. In this zone, the mean value of the ROP is 16.67 [ft/h], which is significantly higher when compared to that which is observed in zone 2. However, in zone 2, the ROP indicates a decreasing trend, while the MSE and WOB indicate an increasing trend, i.e., an inefficient drilling process. In this zone, the mean value of the ROP is 5.48 [ft/h], which is relatively low. The MSE reaches a mean value of 941.24 [kpsi], which is extremely high compared to the mean MSE value of 227.87 [kpsi] (zone 1). This increasing trend occurs due to the high value of the WOB, which, in this case, reflects a low ROP, and most probably indicates an operation beyond...
the foundering point as per Figure 1. The WOB exceeds the mean value of 18.27 [klb] and reaches a maximum value of 42.88 [klb]. This inefficiency causes undesirable effects that will lead to vibrations, drill bit wear, and consequently, an increase in the operation time and cost.

4.2. Drill Rate Test

The drill rate test (DRT) goal, detailed in Section 2, is to ensure an WOB and RPM that result in a safe and efficient drilling. The DRT is a pre-operational test that should always be carried out due to the changes that occur in the drilling of the actual formation, i.e., the lithology and static drilling parameters, such as the drill bit and diameter of the well. For this reason, a DRT must be carried out in an agile and fast way.

The dataset was initially separated by different RPM values (110, 120, 130, 140, and 150 [rev/min]) and afterward, the means of the WOB, ROP, and MSE values were determined for the WOB groups of 3, 5, and 7 [klb]. Figures 4–6 show the relation between the traditional ROP vs. WOB plot and the MSE vs. WOB plot for WOB groups of 3, 5, and 7 [klb], respectively.

Through analyzing Figures 4a, 5a, and 6a, it can be observed that only the curves for 110 and 120 [rev/min] present region II and the inflection point. The inflection point is the maximum point where an increase in the WOB value causes an increase in the ROP value; from this point, a decrease in the ROP occurs (inefficiency, as per Figure 1). The other uncited curves only show region III, indicating an inefficient drilling process, where the increased WOB value causes a decrease in the ROP value.

![Figure 4. WOB groups of 3 [klb]: (a) ROP vs. WOB plot; (b) MSE vs. WOB plot.](image1)

![Figure 5. WOB groups of 5 [klb]: (a) ROP vs. WOB plot; (b) MSE vs. WOB plot.](image2)
Before starting the optimization process, choosing the best combination of the RPM and WOB is necessary. As demonstrated in the previous section, the graphical response for RPMs of 110 and 120 [rev/min] presents a considerable similarity to Figure 2. For this reason, these are the RPMs chosen for the further development of the multi-objective optimization in this study.

The next necessary step is to correlate the response variables with the WOB through regressions. The objective is to obtain a multi-objective optimization that is able to combine the maximum ROP and the minimum MSE, concomitantly. The ROP minimum response will be based on Equation (3) (LTB), while the MSE will be minimized according to Equation (4) (STB), both presented in Section 3. A multi-objective optimization is carried out using Microsoft Excel software version 14,072,685,000 as a base, as shown in Figure 7.

The generalized reduced gradient (GRG) approach is used to solve nonlinear optimization problems and depends on changing the values of the considered variables gradually while monitoring the governing conditions, until the partial derivatives of the target function are equal to zero [60]. The GRG nonlinear solver method was used in this analysis to solve the nonlinear model that combines the maximum ROP and the minimum MSE. To obtain the optimal points, the option “use multiple starts” was used.

The following tables (Tables 1–7) show the results obtained from the multi-objective optimization for RPMs of 110 and 120 [rev/min] and WOB groups of 3, 5, and 7 [klb]. The tables are characterized by different values of weights for the response variables, allowing the operator to choose the best scenario for the current drilling process. Table 1 shows the results of the multi-objective optimization for the grouping of 3 [klb].

Upon comparing the values shown in scenario 1 of Table 1, it is noted that the maximum values reached for the ROP and MSE are 19.14 [ft/h] and 81.99 [kpsi] for an RPM of 110 [rev/min], and 21.14 [ft/h] and 158.30 [kpsi] for an RPM of 120 [rev/min]. Note that an increase in the ROP of 2.00 [ft/h] leads to an increase in the MSE of 76.31 [kpsi] and a decrease in the WOB of 5.78 [kpsi]. This improvement of 2.00 [ft/hr] in the ROP is considerably small for the large increase in the MSE used. Scenario 11 for an RPM of 120 [rev/min] shows good results. For this, an ROP of 20.10 [ft/h] is obtained when applying a WOB of 11.61 [klb]. By comparing these values with scenario 1 for an RPM of 110 [rev/min], it is possible to obtain a better ROP using half the WOB value; however, this leads to an MSE increase of 26.16 [kpsi].

Figure 6. WOB groups of 7 [klb]: (a) ROP vs. WOB plot; (b) MSE vs. WOB plot.
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Therefore, it can be concluded that the combination of an RPM of 120 [rev/min] and lower WOB values (when compared to an RPM of 110 [rev/min]) resulted in better ROP values; however, it caused high MSE values. And high MSE values are not desired, and one should seek the lowest achievable MSE. Table 2 shows the results of the multi-objective optimization for the grouping of 5 [klb].

Through Table 2, it can be seen that the WOB, ROP, and MSE value ranges for an RPM of 110 [rev/min] vary from 21.24 to 22.79 [klb], 21.37 to 21.53 [ft/h], and 63.95 to 69.22 [kpsi], respectively. These results show a good fit of the parameters. Again, a difference in WOB and MSE values is seen when the values presented for an RPM of 110 [rev/min] and for an RPM of 120 [rev/min] are compared. Good ROP values are obtained using a lower WOB; however, this combination of parameters leads to high MSE values at the same time.
which is not desired. Table 2 shows the results of the multi-objective optimization for the grouping of 7 [klb].

<table>
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Table 3 shows similar MSE values for all the scenarios under analysis. However, for an RPM of 120 [rev/min], better ROP values are obtained when a smaller WOB is in place. By analyzing the presented data, scenario 11 shows to be a good option, generating ROP values higher than 20 [ft/h] and MSE values lower than 90 [kpsi] when using a WOB lower than 11 [klb].

<table>
<thead>
<tr>
<th>Weight</th>
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<th>120 [rev/min]</th>
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<td>0.80</td>
<td>0.20</td>
</tr>
<tr>
<td>04</td>
<td>0.70</td>
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<tr>
<td>05</td>
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<tr>
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<td>0.20</td>
<td>0.80</td>
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<tr>
<td>10</td>
<td>0.10</td>
<td>0.90</td>
</tr>
<tr>
<td>11</td>
<td>0.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

The drill rate test combined with the multi-objective optimization proved to be effective and allowed us to visualize different interactions between the ROP vs. WOB, MSE vs. WOB, and MSE vs. ROP for different RPMs. The WOB groups of 5 and 7 [klb] proved to be effective, thus speeding up any possible delays related the data processing and the pre-operational test.

4.4. Analysis of Costs

Ultra-deep drilling operations in the pre-salt fields can reach costs of around USD 1.3 million per day [20,61]. Considering the daily operating cost presented, Table 4 shows the cost and time to drill zone 2 (inefficient zone; exhibited in Figure 3).
The inefficient zone has an extension of 99.49 [ft]. For this depth range, a total operating time of 25.42 [h] was registered, which may reflect to a total cost of approximately USD 1,387,335. This result shows that the ROP for this zone was very low, with mean values of approximately 3.42 [ft/h] or 1.04 [m/h].

Tables 5–7 show the cost and time required to drill zone 2 (inefficient zone) after carrying out the drill rate test (pre-operational test) and multi-objective optimization, using the parameters obtained and presented in Tables 1–3, respectively.

Tables 5–7 show the time, cost, time savings, and cost savings to drilling the inefficient zone through the WOB’s grouping of 3, 5, and 7 [klb] and 110 and 120 [rev/min]. The cost and time to drill this inefficient zone using the parameters obtained from the pre-operational tests ranged from 226,437 to 322,154 [USD] and 4.18 to 5.95 [h], respectively. In addition, when comparing the values shown in Tables 5–7 with the values in Table 4, the cost-saving and time-saving values range from USD 1,056,180 to 1,151,898 and 19.50 to 21.27 [h], respectively.

Table 4. Cost analysis of parameters used during the drilling of zone 2.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>2.30–43.31</td>
<td>1.29–13.97</td>
<td>109.36–151.77</td>
<td>99.49</td>
<td>25.42</td>
<td>1,387,335</td>
</tr>
</tbody>
</table>

Table 5. Cost analysis related to the parameters and values presented in Table 1.

<table>
<thead>
<tr>
<th>110 [rev/min]</th>
<th>120 [rev/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>5.07</td>
</tr>
<tr>
<td>02</td>
<td>5.07</td>
</tr>
<tr>
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<td>5.07</td>
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<td>5.08</td>
</tr>
<tr>
<td>11</td>
<td>5.09</td>
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</tbody>
</table>

Table 6. Cost analysis related to the parameters and values presented in Table 2.

<table>
<thead>
<tr>
<th>110 [rev/min]</th>
<th>120 [rev/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>4.50</td>
</tr>
<tr>
<td>02</td>
<td>4.50</td>
</tr>
<tr>
<td>03</td>
<td>4.50</td>
</tr>
<tr>
<td>04</td>
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<td>10</td>
<td>4.53</td>
</tr>
<tr>
<td>11</td>
<td>4.54</td>
</tr>
</tbody>
</table>
Table 7. Cost and time analysis related to the parameters and values presented in Table 3.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th>120 [rev/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>Cost</td>
<td>Time</td>
<td>Cost</td>
</tr>
<tr>
<td>[h]</td>
<td>[USD]</td>
<td>Savings</td>
<td>[USD]</td>
</tr>
<tr>
<td>0.01</td>
<td>4.76</td>
<td>257,756</td>
<td>20.69</td>
</tr>
<tr>
<td>0.02</td>
<td>4.76</td>
<td>257,958</td>
<td>20.68</td>
</tr>
<tr>
<td>0.03</td>
<td>4.77</td>
<td>258,645</td>
<td>20.67</td>
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<td>0.04</td>
<td>4.80</td>
<td>259,977</td>
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</tr>
<tr>
<td>0.05</td>
<td>4.84</td>
<td>262,196</td>
<td>20.61</td>
</tr>
<tr>
<td>0.06</td>
<td>4.91</td>
<td>265,692</td>
<td>20.54</td>
</tr>
<tr>
<td>0.07</td>
<td>5.01</td>
<td>271,132</td>
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<tr>
<td>0.08</td>
<td>5.17</td>
<td>279,802</td>
<td>20.28</td>
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<tr>
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<td>294,609</td>
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<tr>
<td>0.10</td>
<td>5.95</td>
<td>322,154</td>
<td>19.50</td>
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<tr>
<td>0.11</td>
<td>5.95</td>
<td>322,154</td>
<td>19.50</td>
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</tbody>
</table>

5. Conclusions

In this research, a multi-objective optimization was performed, based on pre-operational drilling tests linked to a new recent methodology aimed at improving the drilling process using a possible ideal combination of the ROP and MSE. This methodology was mainly based in a recreation (play-back methodology) of the usual DRT from a field dataset, from a real pre-salt drilling operation. The main conclusions drawn from this research are as follows:

- The new concept of pre-operational testing based on the MSE showed promise through effective improvements in the drilling processes.
- The combination of the highest ROP and the lowest MSE allows us to perform an efficient drilling operation, preventing machinery and equipment overload, and consequently showing possible ways to improve the operational efficiency.
- The desirability method, as per Derringer and Suich (1980), allowed rooms to optimize drilling process satisfactorily, which may be extended to other operations and scenarios.
- For the WOB intervals of 3, 5, and 7 [klb], a good fit of the parameters was obtained, and as an interesting outcome for the industry, it was determined that a DRT using 5 and 7 [klb] may be sufficient to be applied in a real-time field operation.
- Through the parameters obtained from pre-operational tests, specifically for the data analyzed, it was possible to obtain eventual cost-saving and time-saving values ranging from USD 1,056,180 to 1,151,898 and 19.50 to 21.27 [h], respectively.
- The results of this research can be applied to the exploration of other natural resources, such as natural hydrogen and geothermal sources.

Author Contributions: Conceptualization, D.Z.M.; methodology, D.Z.M. and A.N.; formal analysis, D.Z.M. and A.N.; writing—original draft preparation, D.Z.M.; writing—review and editing, A.N., V.F.D. and M.H.M.; supervision, A.N. All authors have read and agreed to the published version of the manuscript.

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List of Abbreviations

- **D**: Total desirability
- **DHAP**: Downhole annulus pressure
- **DHAT**: Downhole annulus temperature
- **DOT**: Drill rate test
- **DRT**: Drill-off test
- **ECD**: Equivalent circulating density
- **EGS**: Enhanced geothermal system
- **FLOW**: Flow rate
- **GRG**: Generalized reduced gradient
- **HC**: Hydrocarbons
- **L**: Lower limit
- **LTB**: Larger-the-best
- **MD**: Measured depth
- **MSE**: Mechanical specific energy
- **NTB**: Nominal-the-best
- **NTP**: Total non-productive time
- **O–G**: Oil and gas
- **RPM**: Drill string rotary speed
- **ROP**: Rate of penetration
- **SPP**: Standpipe pressure
- **STB**: Smaller-the-best
- **T**: Target value
- **TOB**: Torque-on-bit
- **U**: Upper limit
- **UCSS**: Ultimate confined compressive strength
- **USD**: United States dollar
- **WOB**: Weight-on-bit

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