

DIUNAY ZULIANI MANTEGAZINI

**Pre-operational drilling test applied to carbonate reservoirs: a multi-objective
optimization approach analysis of ROP and MSE**

Diunay Zuliani Mantegazini

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optimization approach analysis of ROP and MSE**

Dissertation presented to the Faculdade de Engenharia e Ciências - Campus de Guaratinguetá (FEG), from the Universidade Estadual Paulista (UNESP), as part of the fulfillment to award the degree of Doctor in Mechanical Engineering.

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Guaratinguetá - SP

2023

M292p	<p>Mantegazini, Diunay Zuliani</p> <p>Pre-operational drilling test applied to carbonate reservoirs: a multi-objective optimization approach analysis of ROP and MSE / Diunay Zuliani Mantegazini - Guaratinguetá, 2023.</p> <p>102 f : il.</p> <p>Bibliography: f. 79-89</p> <p>Thesis (Doctor) – Unesp São Paulo State University, School of Engineering, Guaratinguetá, 2023.</p> <p>Advisor: Prof. Dr. Andreas Nascimento</p> <p>Co-Advisor: Prof. Dr. João Andrade de Carvalho Junior</p> <p>1. Hydrocarbon reservoirs. 2. Oil wells - Drilling. 3. Stratigraphic drilling. 4. Petroleum - Geology. I. Title.</p> <p>CDU 622.323(043)</p>
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DIUNAY ZULIANI MANTEGAZINI

**ESTA TESE FOI JULGADA ADEQUADA PARA A OBTENÇÃO DO TÍTULO
DE “DOUTOR EM ENGENHARIA MECÂNICA”**

**PROGRAMA: ENGENHARIA MECÂNICA
CURSO: DOUTORADO**

APROVADA EM SUA FORMA FINAL PELO PROGRAMA DE PÓS-GRADUAÇÃO

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I dedicate this work to my family.

ACKNOWLEDGMENT

To my parents, Juberto Mantegazini and Maria Aparecida Vignatti Mantegazini, and my sister Dhangeli Zuliani Mantegazini, for the support, education, and advice.

To the Supervisor Prof. Dr. Andreas Nascimento, for the teaching, guidance, competence, professionalism, support, friendship and dedication in developing this dissertation. To co-supervisor Prof. Dr. João Andrade de Carvalho Júnior for the support.

To the São Paulo State University (UNESP) and Post-graduation technical session of FEG for all the assistance, support, and dataset provided.

To the Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES) and National Council for Scientific and Technological Development (CNPq).

This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES) – Financing Code 001.

ABSTRACT

With the discovery of Pre-salt hydrocarbon reservoirs, appeared new challenges. One of the main challenges is the necessity of optimizing drilling processes due to high related operational costs. Drilling costs are considerably high, which leads the Oil and Gas (O&G) industry to search for innovative and entrepreneur methods. The Mechanic Specific Energy (MSE) is a parameter that is being used along drilling operations; coupling of MSE and Rate of Penetration (ROP) is a method that allows identifying ideal conditions during the drilling process aimed at efficiency enhancement. In addition, the performance of the drilling process can be estimated through pre-operational tests, which consist in continuously testing applied drilling mechanic parameters, such as Drill-String Rotary Speed (RPM) and Weigh-On-Bit (WOB), looking for optimum sets would ultimately provide the most desirable ROP. Thus, the goal of this dissertation was to analyze field data from Pre-salt layers operations, using a multi-objective optimization based on a play-back methodology for pre-operational drilling tests, through the ideal combination, simultaneously aiming at the highest possible ROP and the lowest achievable MSE. In addition, the Response Surface Method (RSM) was used to explore the effects of input variables on response variables at a 95% confidence level. The results showed that the new concept of pre-operational tests based on MSE and ROP proved to be effective in the drilling process optimization. The combination between the highest ROP and the lowest MSE allows for performing an efficient drilling process. In terms of parameters setting interval in pre-operational drilling-tests, for WOB, intervals of 5 and 7 [klb] showed to be sufficient for presenting reliable results. Through the parameters obtained from pre-operational tests, it could be estimated eventual cost-saving and time-saving values ranged from USD 1,056,180.72 to 1,151,898.30 and 19.50 to 21.27 [h], respectively.

KEYWORDS: Desirability; Drill-rate test; Mechanical Specific Energy; Pre-salt layers; Oil & Gas.

RESUMO

Com a descoberta dos reservatórios de hidrocarbonetos do Pré-sal, surgiram novos desafios. Um dos principais desafios é a necessidade de otimizar o processo de perfuração devido aos altos custos operacionais. Os custos de perfuração são consideravelmente altos, o que leva a indústria de Petróleo e Gás (O&G) a buscar métodos inovadores e empreendedores. A Energia Mecânica Específica (MSE) é um parâmetro que está sendo utilizado ao longo das operações de perfuração; o acoplamento da MSE e da Taxa de Penetração (ROP) é um método que permite identificar condições ideais durante o processo de perfuração visando o aumento da eficiência operacional. Além disso, o desempenho do processo de perfuração pode ser estimado por meio de testes pré-operacionais, que consistem em testar continuamente parâmetros mecânicos de perfuração, como a velocidade de rotação da coluna de perfuração (RPM) e o peso aplicado sobre a broca (WOB), procurando obter conjuntos ótimos que forneçam a ROP desejável. Dessa forma, o objetivo desta dissertação de doutorado foi analisar os dados de campo das operações de perfuração no Pré-sal, utilizando a otimização multi-objetivo baseada na metodologia play-back para testes pré-operacionais, através da combinação ideal, visando simultaneamente o maior ROP possível e o menor MSE alcançável. Além disso, o Método de Superfície de Resposta (RSM) foi usado para explorar os efeitos das variáveis de entrada sobre as variáveis de resposta a um nível de confiança de 95%. Os resultados mostraram que o novo conceito de testes pré-operacionais baseados na MSE e ROP se mostrou eficaz na otimização do processo de perfuração. A combinação entre a mais elevada ROP e a menor MSE permite realizar um processo de perfuração eficiente. Em termos de intervalo de parametrização em testes de perfuração pré-operacionais, para WOB, os intervalos de 5 e 7 [klb] mostraram-se suficientes para apresentar resultados confiáveis. Através dos parâmetros obtidos nos testes pré-operacionais, pode-se estimar eventuais valores de economia de custo e tempo variando de 1.056.180,72 a 1.151.898,30 [USD] e de 19,50 a 21,27 [h], respectivamente.

PALAVRAS-CHAVE: Desejabilidade; Teste da taxa de perfuração; Energia Mecânica Específica; Pré-sal; Óleo & Gás.

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LIST OF ABBREVIATIONS AND INITIALS

ABM	Air-Based Muds
ANN	Artificial Neural Networks
ANP	Brazilian National Agency of Petroleum, Natural Gas and Biofuels (<i>Agência Nacional do Petróleo, Gás Natural e Biocombustíveis</i>)
BOP	Blowout Preventer
BTU	British Thermal Units
BYM	Bourgoyone and Young model
CAPES	Coordination for the Improvement of Higher Education Personnel (<i>Coordenação de Aperfeiçoamento de Pessoal de Nível Superior</i>)
CCS	Confined Compressive Strength
DOT	Drill-Off Test
DRT	Drill-Rate Test
EFF _M	Drilling Efficiency Factor
EIA	Energy Information Administration
EOB	End-Of-Build
EOD	End-Off-Drop
FEG	Faculty of Engineering and Sciences - Campus of Guaratinguetá (<i>Faculdade de Engenharia e Ciências - Campus de Guaratinguetá</i>)
FLOW	Flow-Rate
GRG	Generalized Reduced Gradient
HAC	Heteroscedasticity and Autocorrelation Consistent
HCCME	Heteroscedasticity Consistent Covariance Matrix Estimators
HPHT	High Pressure High Temperature
HSME	Hydro-Mechanical Specific Energy
IQR	Interquartile range
KOP	Kick-Off Point
LTB	Larger-The-Better
LWD	Logging While Drilling
MD	Measured Depth
MLR	Multiple Linear Regression
MSE	Mechanical Specific Energy
MWD	Measurement While Drilling

NPT	Non-Productive Time
NTB	Nominal-The-Best
OBM	Oil-Based Muds
O&G	Oil and Gas
PDC	Polycrystalline Diamond Compact;
PDM	Positive Displacement Motor
ROP	Rate of Penetration
RSM	Response Surface Methodology
RPM	Drill-String Rotary Speed
SBM	Synthetic-Based Mud
SEOBB	Southeastern Offshore Brazilian Basins
SSI	Stick Skip Index
STB	Smaller-The-Better
TOB	Torque-On-Bit
UCS	Unconfined Compressive Strength
WBM	Water-Based Mud
WOB	Weight-On-Bit

LIST OF SYMBOLS

a_1	Formation strength and drilling fluid properties coefficient
a_2	Normal compaction trend coefficient
a_3	Under-compaction and pore pressure coefficient
a_4	Differential pressure coefficient
a_5	Constant dependent on drilling conditions and WOB behavior
a_6	Constant dependent on drilling conditions and rotary speed behavior
a_7	Teeth-cutters wear coefficient
a_8	Hydraulic coefficient
A_b	Drill-bit cross-section area
D_b	Drill-bit diameter
g_c	Mass conversion
H_L	Lower quartile
H_U	Upper quartile
K	Constant dependent drill-bit dullness, formation and drilling conditions
L	Low limit
T	Target
U	Upper limit
X	Input variables
X_1	WOB
X_2	RPM
X_3	TOB
X_4	FLOW
Y	Response variable
Y_1	ROP
Y_2	MSE
β_0	Constant coefficient
β_j	Linear coefficient
β_{jj}	Quadratic coefficient
β_{ij}	Interaction coefficient
η	Efficiency of PDM
n	Dummy factor for energy reduction

μ_b	Bit-Specific Coefficient of Sliding Friction
μ_s	Coefficient of friction of drill-string
γ_b	Inclination of the bottom hole
ΔP_b	Pressure drop across the drill-bit
ΔP_m	Differential pressure across the drill-bit

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1 INTRODUCTION

The registered increasing demand for energy in general and hydrocarbons within the next few years, forecasted by different energy outlook reports in recent years, also supported the Oil and Gas (O&G) industry in exploring reserves in more challenging environments (NASCIMENTO, 2016; BP, 2023; EIA, 2023). Drilling wells in challenging environments involves high costs, mostly related to well construction and drilling processes (BARBOSA et al., 2019). Thus, it is still very important to focus on efficiency enhancements, which may allow potential time saving and operational costs reduction (SOARES; DAIGLE; GRAY, 2016).

The exploration of Pre-salt layers serves as an example of the challenges and difficulties faced during drilling activities. In this case, the challenges are related to the operations in ultradeep water, reservoirs located below 5,000 [m] and thick evaporite layers, high pressure and high temperature, offshore located (up to 300 [km] of the coast), and considerably abrasive carbonate rock reservoir (NASCIMENTO et al., 2015). In addition to the challenges indicated above, the definition of optimum drilling parameters while drilling, such as Drill-String Rotary Speed (RPM), Weight-On-Bit (WOB), Torque-On-Bit (TOB), and Flow-Rate (FLOW), it is still important and a not so a trivial activity. Within the O&G industry, these are common nomenclatures and respective abbreviations used when referring to such parameters.

The main drilling performance indicators are the rate of penetration (ROP) and Mechanical Specific Energy (MSE). ROP is an indication of how fast the well is drilled in terms of the length of hole drilled per unit of time (SOARES; DAIGLE; GRAY, 2016). While the MSE measures the amount of energy necessary to remove a unit volume of rock (TEALE, 1965). The combination between the highest ROP and the lowest MSE has not only the potential to reduce the costs of the drilling process, but also to reduce operating time. Once the drilling time is reduced, the time in which geological formations are exposed is also reduced, reducing the chances of destabilization and operational risks (GANDELMAN, 2012).

ROP prediction has been the subject of several types of research over the years. The first studies began in the 1960s. Maurer (1962) developed an ROP model for cone drill-bits, using parameters such as WOB, RPM, drill-bit diameter, and Uniaxial Compressive Strength of rock (UCS). Bingham (1965) used the drill-bit diameter, WOB, and RPM in his model, while Eckel (1967) incorporated the drilling mud effects. Bourgoyne and Young (1974) created one of the most complex ROP models using several parameters, such as the WOB,

RPM, drill-bit diameter, drill-bit tooth wear, formation strength, depth, compaction, pore pressure, differential pressure, and the effect of drill-bit hydraulic jet impact force. Drilling models have been improved with technological advances, Arabjamaloei and Shadizadeh (2011) used Artificial Neural Networks (ANN) to predict ROP through field data obtained in an Iranian oil field. While Hegde and Gray (2017) used machine learning to predict and increase ROP, through input parameters such as RPM, WOB, and FLOW.

The first relation for calculating MSE was proposed by Teale (1965) for a rotary system based on experimental results. The main disadvantage of the equation presented by Teale is that it requires TOB measurement. Considering the problem presented, Pessier and Fear (1992) introduced the Bit-Specific Coefficient of Sliding Friction (μ_b) to express TOB as a function of WOB. Later, the equation originally introduced by Teale was adjusted by Dupriest and Koederitz (2005) to include the Drilling Efficiency Factor (EFF_M). In the last decade, Chen et al. (2014) developed a relation between the WOB measured at the surface and the WOB measured at the bottom of the well. While Chen et al. (2016) developed a new model for rotary drilling using a Positive Displacement Motor (PDM).

The drilling process performance can be estimated using pre-operational tests. The pre-operational tests, such as the Drill-Rate Test (DRT) and Drill-Off Test (DOT) determine the best combinations of parameters for drilling a given formation. The test consists in continuously increasing the WOB, keeping the RPM fixed in a short depth interval to obtain the ROP values (SOUTO; NASCIMENTO, 2016). However, it is important to enhance that the drilling process optimization doesn't consist simply in obtaining the highest ROP. In fact, it is necessary to search for parameters that allow drilling a phase of the well in the shortest time. Thus, the objective of this research is to obtain a multi-objective optimization capable of optimizing the drilling process, through the combination between the highest ROP and the lowest MSE, by the ideal combination of operating conditions.

1.1 OBJECTIVES

This dissertation aims to analyze and evaluate how the parameters of the drilling process affect the ROP and MSE and consequently the time and cost of the process, based on the following specific objectives:

- Analyze a field dataset from a real Pre-salt drilling operation;

- Study and apply new techniques and research about drilling optimization from drilling mechanics parameters;
- Study a multi-objective optimization based on a play-back methodology for pre-operational drilling tests;
- Develop and apply a new concept of pre-operational tests based on MSE;
- Develop and apply a methodology based on the desirability method proposed by Derring and Suich;
- Cost and time analysis based on values of mechanical parameters obtained from multi-objective optimization.

1.2 DISSERTATION STRUCTURE

The dissertation is structured as follows:

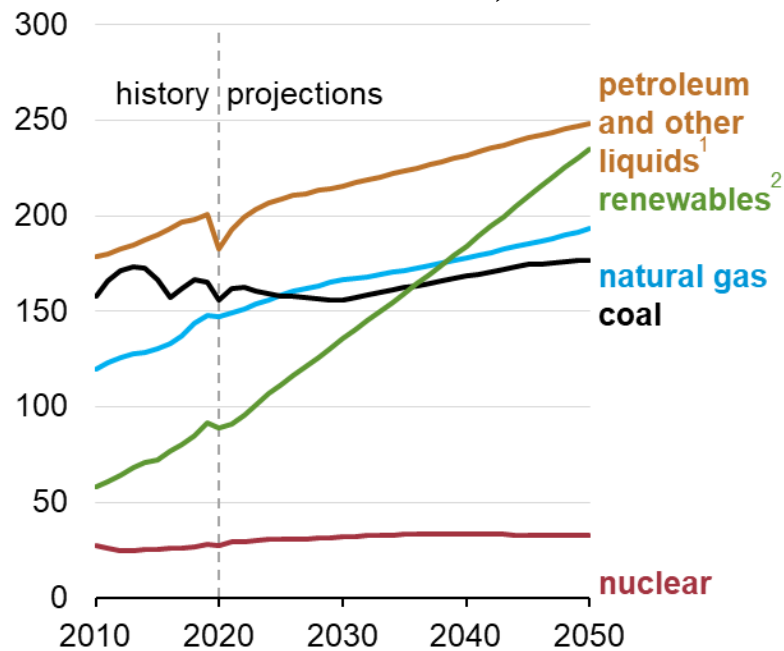
- Introduction: presents the relevance and importance of the subject in the well drilling process;
- Literature review: presents a review of the concepts used in the dissertation;
- Methodology: presents the acquisition and treatment of the dataset, in addition to the methodology developed for multi-objective optimization;
- Development: presents data analysis through the pre-operational test, multi-objective optimization, and surface response method;
- Conclusion: presents a consolidation of results.

2 LITERATURE REVIEW

2.1 PRE-SALT

Despite the great efforts to replace them with renewable energy sources, fossil energy sources continue to play an important role in the global energy context due to the need to meet the increasing energy demands (NASCIMENTO et al., 2015). The Energy Information Administration (EIA) predicts that petroleum and other liquid fuels remain the largest source of primary energy used energy source in the world by 2050, as per Figure 1.

Figure 1 - Primary energy consumption by energy source in the world (quadrillion British thermal units).

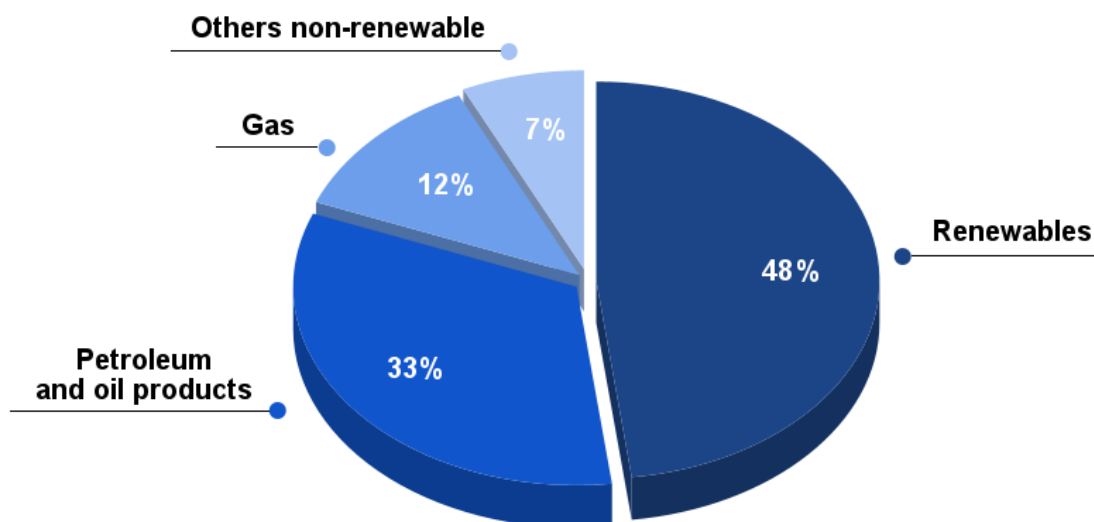


¹ Includes biofuels.

² Electricity generation from renewable sources is converted to Btu at a rate of 8,124 Btu/kWh.
Source: EIA (2021).

In Brazil, the O&G sector plays an important role, the country is the eighth largest crude oil and condensate producer and the seventh largest crude oil exporter in the world (ABELHA, 2022). Figure 2 shows the relevance of the O&G industry in Brazil.

Figure 2 - Relevance of the O&G industry in Brazil.

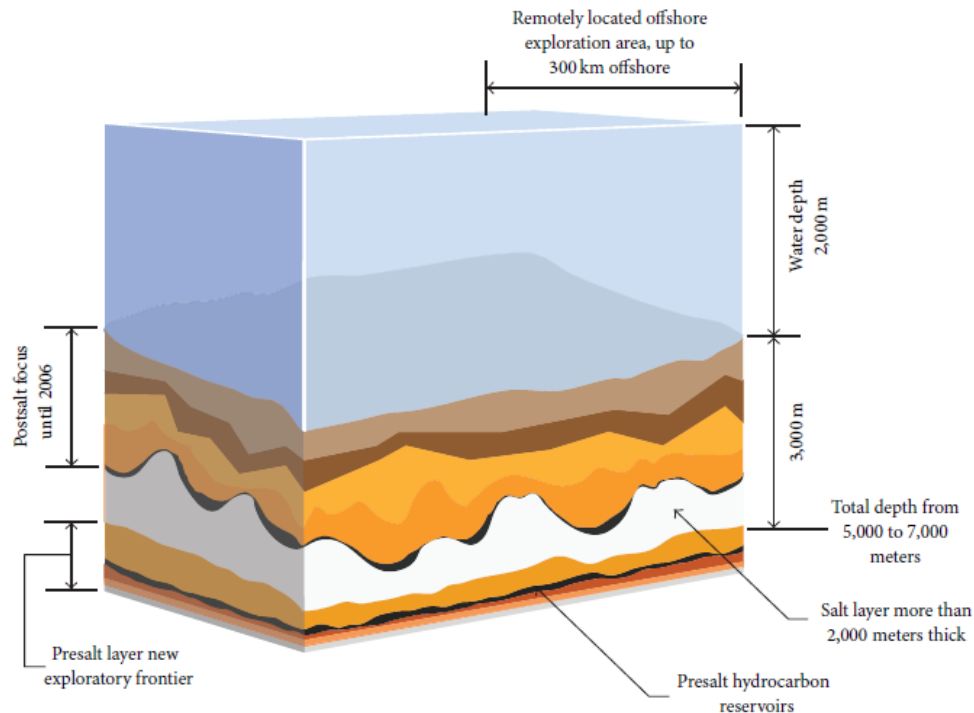


Source: Adapted from Abelha (2022).

The Pre-salt layer is a sequence of sedimentary rocks formed about 150 million years ago during the separation of the ancient continent Gondwana into the present-day South American and African continents (FRANÇA et al., 2021). Between the two present-day continents, large depressions were formed, which turned into large lakes. Large amounts of organic matter (mainly from microscopic algae) have accumulated in the deeper regions of these lakes. The mixture of this organic matter with sediments formed the source rocks. The organic matter was transformed into oil and gas, in a process called “generation”, which involves high temperatures and pressures. In the non-deeper parts, on large lake islands, limestone shells, and stromatolites (types of algae that form limestone rocks) were deposited, forming reservoirs.

After the deposition of the stromatolite layers, the large lakes were connected to the oceans, passing from lacustrine systems to a restricted marine system, which caused the formation of an extensive gulf. The arid climate predominant at that time and the intense evaporation of the marine water that invaded these lake depressions, lead to the accumulation of salts, which resulted in the salt layer that worked as a seal to prevent the oil from escaping and arriving at the surface (PRÉ-SAL PETRÓLEO, 2022). The Pre-salt reservoirs are located at a depth of 5–7 [km] under a salt layer up to 2 [km] thick (FRANÇA et al., 2021). The detailed localization of the Pre-salt layer is shown in Figure 3.

Figure 3 - Location of the pre-salt layer.



Source: Nascimento et al. (2015).

The pre-salt carbonate reservoir has large accumulations of oil with high commercial value (PETROBRAS, 2022). The production of petroleum in the Pre-salt passed from approximately 41,000 barrels per day in 2010 to 2.0 million barrels per day in 2020 (PRÉ-SAL PETRÓLEO, 2022). Pre-salt exploration has increased dramatically due to advances in legislation, regulation, and technology. A process that began in 2016 when Petrobras left the only Pre-salt operator with Law 13,365/2016, actually 72% of the exploratory blocks are operated by non-Petrobras companies.

The most important oil region in Brazil is called Southeastern Offshore Brazilian Basins (SEOBB), which is composed of Campos, Santos, and Espírito Santo Basins (BARRA et al., 2021; LOUBACK et al., 2021). Figure 4 presents the location of the SEOBB.

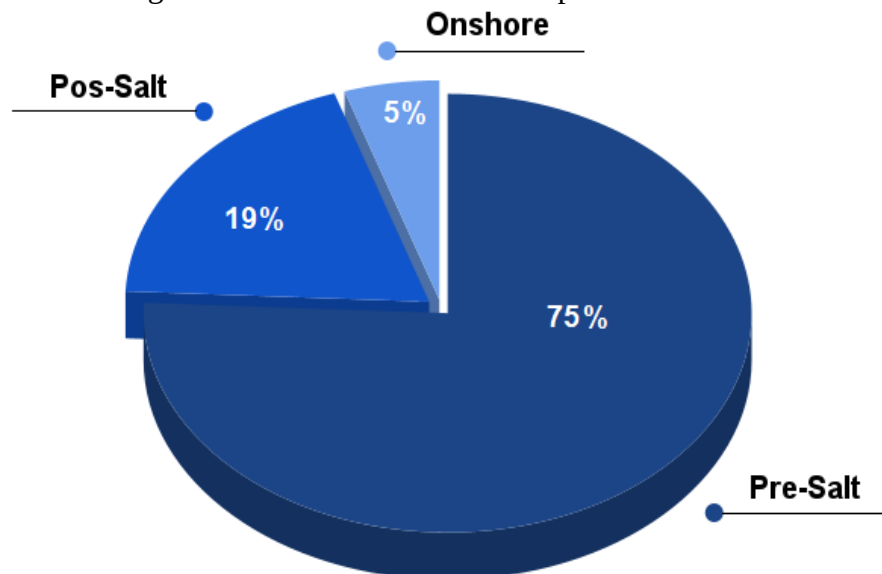
Figure 4 - Location of the SEOBB.



Source: Fernandez-Ibanez et al. (2022).

The Santos Basin is located between latitudes 23°S and 28°S and longitudes 40°W and 47°W and has an extension of 350,000 [km²] and has several large oil fields in the Pre-salt (FERNANDEZ-IBANEZ et al., 2022; VALLE et al., 2021). Nine of the ten wells with the highest production in Brazil are located in this region. The main form of O&G exploration in Brazil is offshore, as per Figure 5, which requires a high level of technological development and innovation.

Figure 5 - Main forms of O&G exploration in Brazil.



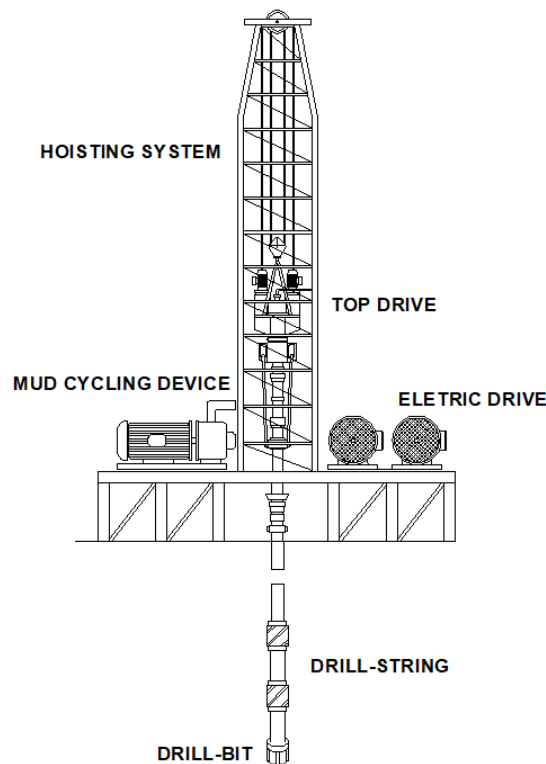
Source: Adapted from Abelha (2022).

Due to the large volume of petroleum found in the Pre-salt, several researchers have searched for methods to reduce costs and the average time to build the well, with operational and environmental safety. However, this geology has high heterogeneity, low permeability, and very high abrasiveness, in addition to reservoir complexity.

2.2 DRILLING EQUIPMENT

The rotary drilling system is the widely used method to oil well drilling. The required TOB for drill-bit rotation and rock destruction is supplied at the surface by the top drive and transmitted to the drill-bit through the drill-string (BAKHTIARI-NEJAD; HOSSEINZADEH, 2017). Figure 6 shows a schematic view of a rotary drilling rig.

Figure 6 - Schematic view of a rotary drilling rig.



Source: Author (2023).

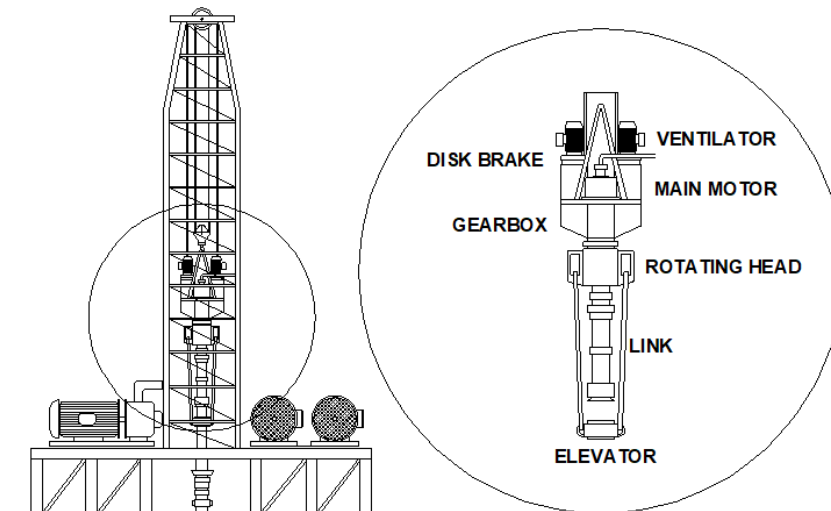
A drilling rig has different parts, which can be classified according to their functions: load support, energy generation and transmission, load movement, rotation, safety, circulation, and monitoring system. The analysis of these different parts is the basis for the control of the drilling rig (NOBAHAR SADEGHI et al., 2019). In the following, the main systems will be detailed.

2.2.1 Rotary system

The rotary system is responsible for transmitting TOB and RPM through the drill-string to drill-bit. The conventional rotary systems used the rotary table and Kelly to turn the drill-string. However, these equipments were replaced by top drive.

The top drive allows the rotation to be transmitted directly to the top of the drill-string by a motor suspended from the hook. Thus, the speed of drill-bit is determined by the output speed of the top drive (SUN; SHI; WANG; YAO, 2018). The schematic drawing of the top drive is shown in Figure 7.

Figure 7 - Schematic drawing of the top drive.



Source: Author (2023).

The use of the top drive optimizes the drilling process by reducing equipment downtime. The top drive allows tasks such as changing the drill-bit, pipe connections and removing the drill-string from the well to be realized more efficiently, directly impacting the calculation of the cost per meter drilled (THOMAS, 2001).

There is also the possibility of drilling using the downhole drilling motor. This system uses the hydraulic power of drilling fluid to drive the rotor inside the stator and converted it into rotational movement (RANJBAR; SABABI, 2012).

2.2.2 Well safety system

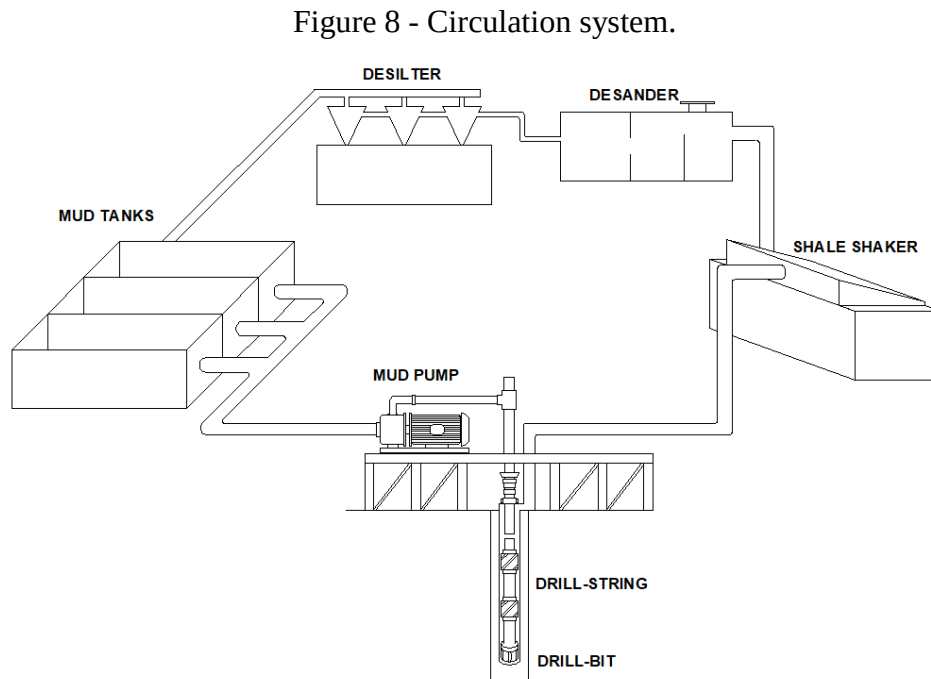
The safety system is composed of equipment that allows for the closing and control of the well to avoid problems such as kicks and blowouts. Kick is a problem characterized by the migration of formation fluids into the well, while the blowout is characterized by an uncontrolled flow (ABIMBOLA; KHAN; KHAKZAD, 2014). The most important equipment in well control is the BOP, whose function is to prevent or mitigate natural disasters due to loss of well control.

The well safety system is composed of the wellhead and preventers, as detailed below:

- Wellhead: unit at the surface of the well, which controls pressure, and provides the structural interface for the drilling and production equipment;
- Preventers: a large valve projected to seal, control, and monitor the wells.

2.2.3 Circulation system

The circulation system is responsible for the circulation and treatment of the drilling fluid. The system is composed of pumps, mud tanks, and mixing and separation equipment (shale shaker, desander, desilter), as shown in Figure 8.



Source: Author (2023).

The drilling fluid has several functions, including transporting the solids generated by the drill-bit to the surface and transmitting hydrostatic pressure to the walls of the well. Drilling fluid is pumped through the drill-string to the drill-bit, where it returns to the surface through the annular space. During this process, the fluid transports solid materials, as well as gases that are incorporated with it, requiring an adequate treatment to adjust properties (THOMAS, 2001).

2.2.4 Monitoring system

Monitoring systems contain equipment that provides the necessary information to control drilling operations in real-time, such as manometers, load cells, and drilling recorders. Obtaining knowledge through the data obtained by monitoring equipment is a challenging task that requires advanced modeling techniques, in addition to intuition and human experience. Measurement of parameters such as WOB, RPM, TOB and FLOW helps the process. However, the most important indicator used in the drilling process is the ROP, which provides important information to assess changes in formations, drill-bit wear, and the adequation of drilling parameters (THOMAS, 2001).

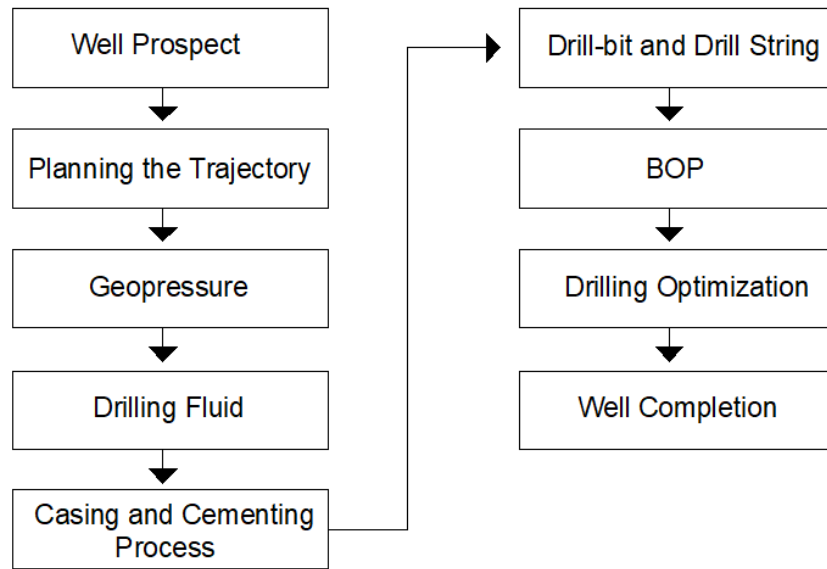
In addition, there are some orientation tools such as Measurement While Drilling (MWD), single shot and multishot. MWD allows immediate and continuous recording of the inclination and direction of the well in the form of pressure pulses through the drilling fluid (KLYUCHNIKOV et al., 2019).

2.3 WELL DESIGN

Due to the higher complexity of the exploited O&G reservoirs, optimizing the well construction process to its most efficient form makes it possible to reduce costs (SHOKRY; ELGIBALY, 2021). Thus, the oil industries have focused part of their efforts on the development of methodologies applied to the oil wells design.

The elaboration of the well design is one of the planning stages for its construction, in which the drilling and completion phases are detailed. Figure 9 shows the workflow that can be followed for the elaboration of a well design.

Figure 9 - Workflow for a well design.



Source: Adapted from Rocha (2009).

In the sequence, the steps will be described according to Thomas (2001) and Rocha (2009).

2.3.1 Well prospect

The discovery of a new accumulation of hydrocarbons involves several studies and analyzes of geological and geophysical data from the sedimentary basin. The design of a well is initiated by the geological study of the area. In this stage, the geological scenario with the highest probability of oil existence is studied, and a historical analysis of wells already drilled in the region is carried out, through the following methods:

- Surface geology: process characterized by recognizing and delimiting sedimentary basins and identifying structures capable of accumulating hydrocarbons by mapping the rocks that outcrop on the surface;
- Aerophotogrammetry and photogeology: Aerophotogrammetry and photogeology: aerophotogrammetry is used to construct topographic maps through aerial photos and satellite images. Photogeology is a process based on aerial photos to identify faults, folds, and dips in the geological layers;
- Subsurface geology: based on analyses of geological data obtained from an exploratory well. This method involves the analyses of drilled formations, description of rock samples collected during the drilling process, construction of structural maps

through the correlation between information from different wells, and analyses and recognition of fossils found in rocks;

- Potential methods: gravimetry and magnetometry analyses use, respectively, the intensity of the Earth's gravitational and magnetic fields to obtain properties of rocks in the subsurface. The variation of density in the subsurface is of interest in gravimetric analyses, allowing obtain data about the sedimentary basin thickness. Magnetic prospecting is used to measure small variations in the intensity of the Earth's magnetic field, which originate in an irregular distribution of magnetized rocks in the subsurface;
- Seismic methods: this prospecting method is widely used by the oil industry, providing a high resolution of subsurface geological features that can contain accumulations of hydrocarbon. This method is based on measurements of transit time and amplitude of waves refracted or reflected at the subsurface formations. These properties are related to the acoustic and elastic properties of the rocks that form the wave propagation environment.

2.3.2 Planning the trajectory

Based on geological information, depth knowledge, and expected geometry for the reservoir, it is possible to calculate and define the best trajectory for the well. The well deviates naturally from the vertical, if this deviation exceeds an inclination limit, which is usually 5°, corrective actions must be taken.

Several factors cause the deviations in the well trajectory, such as variations in the formation characteristics, sudden changes in the WOB, large well diameter for the commands used, drilling with unstabilized columns, and unbalanced drilling parameters. In addition, this tortuosity brings severe problems to the process such as excessive pipe wear, gravel deposition, drag increase, buckling and difficulty in casing string descending (WANG; GAO, 2016; BRITO; PEREYRA; SARICA, 2017). Directional drilling is a method in which the well is purposefully diverted to reach a particular location in the reservoir. Directional wells are drilled for several reasons:

- Control a blowout well by drilling relief wells;
- Reach reservoirs that are below inaccessible locations;
- Deviate the well's trajectory from a geological accident;

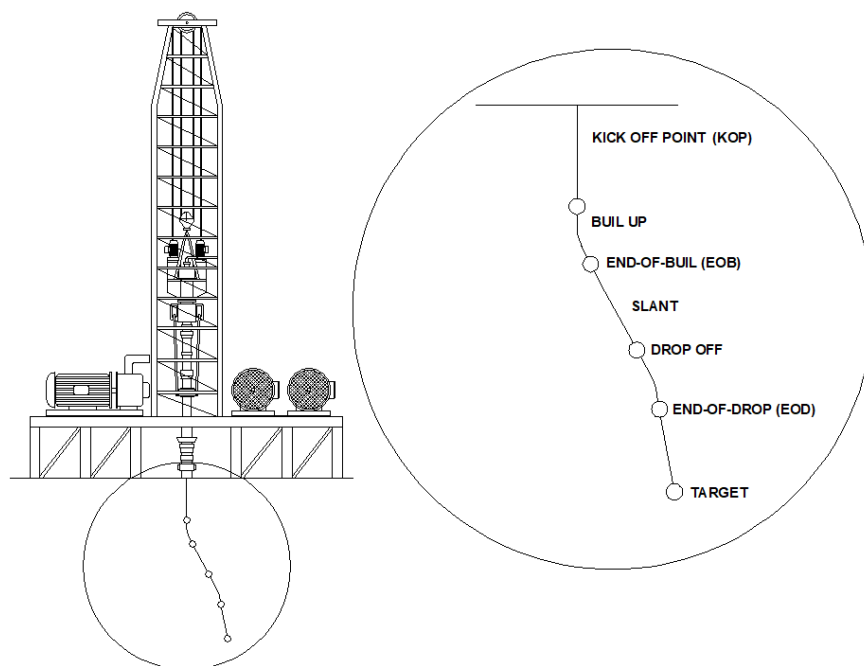
- Drilling multiple wells from the same point;
- Deviate wells that had the final section lost due to operational problems.

Directional wells can be grouped into three types:

- Type I: deviation point is shallow and the inclined section continues until reaching the target;
- Type II: deviation point is also shallow and the inclined section continues until the projected lateral displacement is reached. In the sequence, the well is again deviated to vertical and so on until reaching the goal;
- Type III: similar to type I, but the objective is reached in the slant increase phase.

The main characteristics of directional wells that must be considered during the project are shown in Figure 10.

Figure 10 - Basic points of a directional well trajectory.



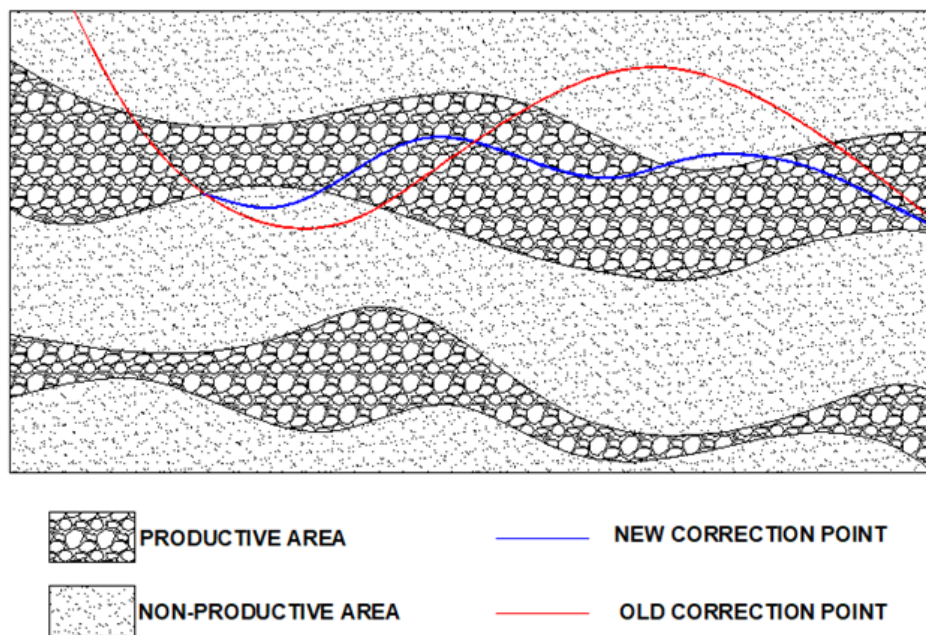
Source: Adapted from Rocha (2009).

- Kick-Off Point (KOP) is the beginning of the angle gain section;
- Build-up is the section where angle gain occurs, while the end of the angle gain section is called End-Of-Build (EOB);

- Slant section is a section whose angle is maintained until the objective is reached, or until there is a change;
- Drop-off begin is the depth where the well starts to lose angle, if necessary;
- Drop-off section, in this section, occurs the angle loss, and the end of the angle loss section is called End-Of-Drop (EOD).

Special strategies and tools are needed to redirect the well in question. For directional drilling, the use of downhole drilling motors in association with MWD made deviation operations simpler and more economical. In these cases, the engineers use data recorded by physical sensors to correct the well trajectory, as can be seen in Figure 11.

Figure 11 - Trajectory correction effect.



Source: Author (2023).

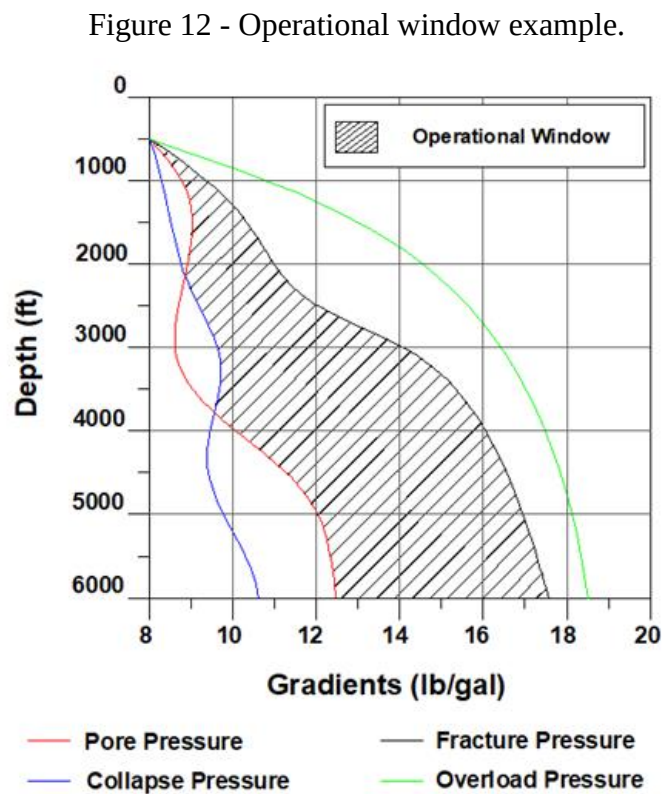
However, the sensors are located more than 15 [m] away from the drill-bit, which can cause a loss in well productivity (KLYUCHNIKOV et al., 2019). In addition to vertical and directional wells, there are horizontal wells. The horizontal well is characterized by a straight section drilled horizontally inside the producing formation. The objective of this technique is to maximize the production and recovery of hydrocarbons and minimize the cost per volume of operators (AL-BLEHED; HAMADA, 1999; BECKER; GARDINER, 1999).

2.3.3 Geopressure

The geopressures study consists of calculating the tensions and pressures existing in the subsurface to avoid rock failure, such as:

- Overload pressure: the overload pressure can be obtained by the sum of the weight of all rock layers superimposed on a determined rock element in the subsurface;
- Pore pressure: characterized as the pressure of the fluid contained in the pore spaces of rock. The pore spaces are occupied by fluids such as gas, oil or water;
- Collapse Pressure: rock failure can cause a deformation in the diameter of the well or even the total collapse of the well. The main consequence is the increased torque in the drill-string and entrapment by wedging;
- Fracture pressure: the fracture pressure can cause rock failure by traction. The operational consequences are landslides or the loss of drilling fluid into the formation.

The overload, pore, collapse, and fracture pressure determine the well's operational window. The operational window determines the range of drilling fluid pressure necessary to maintain the well's integrity, as shown in Figure 12.



Source: Adapted from Rocha (2009).

The fracture pressure and pore pressure are the main parameters analyzed in well design (MAHETAJI; BRAHMA; SIRCAR, 2020). The annulus bottom hole pressure needs to be higher than the pore pressure to avoid the kick, and smaller than the fracture pressure to avoid drilling fluid loss and formation damage (VEGA et al., 2018).

2.3.4 Drilling Fluid

The drilling fluid is fundamental for the drilling operations (AADNOY et al., 2009). The fluid is pumped through the drill-string and exits in the downhole through the holes in the drill-bit and returns to the surface (MAGALHÃES et al., 2016). The main functions of the fluid are to transmit hydrostatic pressure to the well, transport the gravels generated by the drill-bit to the surface, cool the drill-bit and drill-string and transmit electrical signals from downhole devices (BOURGOYNE et al., 1986). Returning to the surface, the fluid is subjected to different treatments, to return to the initial physical-chemical characteristics and to ensure functionality (RAMÉZANI et al., 2015).

The type of fluid used depends on parameters such as depth, drilled formations and well pressure (RAMÉZANI et al., 2015). One of the functions of the fluid is to transmit hydrostatic pressure to the well. If the hydrostatic pressure is lower than the pressure of the confined fluid in the formations and this formation is permeable, those fluids will into the well. If this inflow is controllable, the well is in kick, if uncontrollable, it is in a blowout. The common causes of kicks are insufficient mud weight and incorrect filling of the well during the maneuvering operation. When removing the drill-string from the well, the volume of steel removed must be substituted by an equivalent volume of mud, to maintain the same hydrostatic pressure at the bottom of the well.

The well cleaning is extremely important, maintaining the appropriate conditions and carrying away the solids generated by the drill-bit. If there is an accumulation of rock fragments in the annular space, that can cause serious operational problems, such as the obstruction of the annular space, excessive drag and pressure loss (ARAGAO et al., 2005). One of the ways to avoid the accumulation of gravel in the downhole is to use an ideal flow-rate.

2.3.4.1 Drilling fluid properties

The fluids used during the drilling process can be composed of a complex mixture of solids, liquids, chemicals and even gases (THOMAS, 2001). Fluids are designed to be chemically stable, pumpable, and inert in relation to producing rocks. They are used to stabilize the well, facilitate the gravel separation and keep solids in suspension when at rest. The fluid should also accept any type of physical and chemical treatment, prevent corrosion and abrasion of the equipment, facilitate geological interpretations, and cost compatible with the operation.

The controllable properties of fluids can be classified into physical and chemical. The physical properties are density, rheological parameters, gel strength, filtration, and solids content, while the chemical properties can be described by pH, chloride and bentonite contents, and alkalinity.

2.3.4.2 Classification of drilling fluids

Drilling fluids, also known as muds, are classified into four main types, namely: Water-Base Muds (WBM), Oil-Based Muds (OBM), Air-Base Muds (ABM), and Synthetic-Based Muds (SBM).

- Water-Based Mud (WBM): its function is to provide dispersion for colloidal materials. Clays and polymers control viscosity, yield strength, and gel strength. Adequate mixtures promote good gravel removal and structural stability to the well. In this case, the chemicals added to the fluid can be alkalizing agents and pH controllers, dispersants, filtrate reducers, flocculants, polymers, surfactants, calcium and magnesium removers, and bactericidal;
- Oil-Based Mud (OBM): it is generally composed of liquid hydrocarbons. These fluids are less used due to the high initial cost and pollution degree. The oil-based mud characteristics are high inhibition degree about active rocks, low corrosion, controllable properties above 350 to 500 [°F], high lubricity degree, and a wide range of density variation. These fluids are particularly suitable for HPHT well drilling (high pressure and high temperature), clayey sheet, halite salt, sylvite, carnallite, and sandstone formations, and also for directional wells and formations with a low pore or fracture pressure. However, the use of oil-based muds entails difficulties to detect gas,

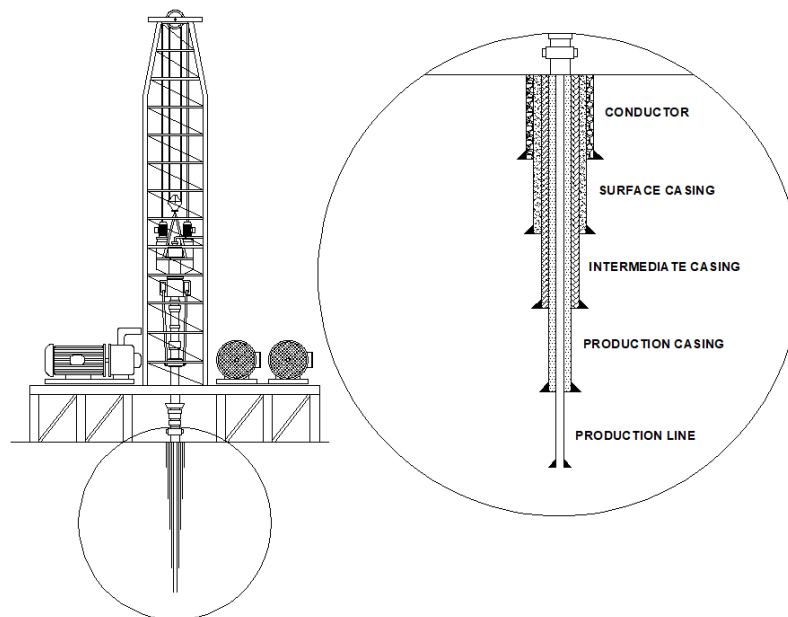
a lower ROP, higher pollution degrees, lower profiles number that can be executed, difficulty in loss circulation control, and higher initial cost;

- **Air-Based Mud (ABM):** recommended in situations where fluids with a low density are needed, such as in areas with severe load loss and production formations with low pressure or high susceptibility for damaged. This fluid type uses only compressed air or nitrogen at formations that do not produce large water amounts and do not contain hydrocarbons;
- **Synthetic-Based Mud:** Those fluids have a non-Newtonian behavior and are dependent on time and shear-rate (BALDINO et al., 2018). Depending on the composition, the synthetic-based mud can be highly toxic. Therefore, the contaminated gravel must be decontaminated before disposal (PETRI et al., 2015).

2.2.5 Casing and cementing process

During the planning process, the number of phases of the well is defined. The phase numbers depend on the zone characteristics to be drilled and the final well depth. These characteristics are determined as a function of the pore and fracture pressure gradient (ELYASI et al., 2014). Figure 13 shows the oil well phases.

Figure 13 - Oil well phases.



Source: Author (2023).

The drilling process begins with a larger diameter which is reduced in each phase until the depth of interest is reached. To drill a well with variable diameters it is necessary to use specific size drill-bits for each diameter phase (THOMAS, 2001). In the following, each phase is described by Thomas (2001) and Rocha (2009):

- Conductor casing: The major function of conductor casing is to support unconsolidated surface sediments and provide a conduit for the drilling fluid. The conductor casing used in offshore wells has typical diameters of 36", and 30";
- Surface casing: it is carried out to prevent the collapse of unconsolidated formations, support the BOP weight and other casing columns and protect water reservoirs. The surface casing used in offshore wells has typical diameters of 22", 20", and 13 3/8";
- Intermediate casing: this phase is intended to isolate and protect high or low-pressure areas, loss circulation, mechanically unstable formations, and formations with corrosive or contaminant fluids. The intermediate casing used has typical diameters of 3/8", 9 5/8", and 7";
- Production casing: a pipe network is used for oil extraction after drilling the oil well, allowing hydrocarbons to be conducted to the surface safely and economically. The production casing typically used has diameters of 9 5/8", 7", and 5 1/2";
- Liner: it is a short casing column, which is anchored above the last casing and covers the downhole. The liner typically used has diameters of 16", 13 3/8", 11 3/4", 9 5/8", 7", and 5 1/2".

According to Thomas (2001), the functions of the casing string are to prevent well collapse, water contamination, allow the drilling fluid return to the surface, control fluid pressures, prevent fluid migration from formations, support wellhead safety equipment, and lodge artificial lifting equipment. However, the column must have strength according to the request, dimensions compatible with future activities, be waterproove, and resistant to corrosion and abrasion.

2.2.6 Drill-bits and drill-string

The drill-bit function is to promote the rupture and disaggregation of rock layers. Drill-bit action is defined through the contact force applied to the cutting tool on the rock surface, generating tensions and, consequently, deformations in the contact área (KRÚPA et al., 2018). For the determination of the ideal drill-bit diameter guidelines are used (BYROM, 2014):

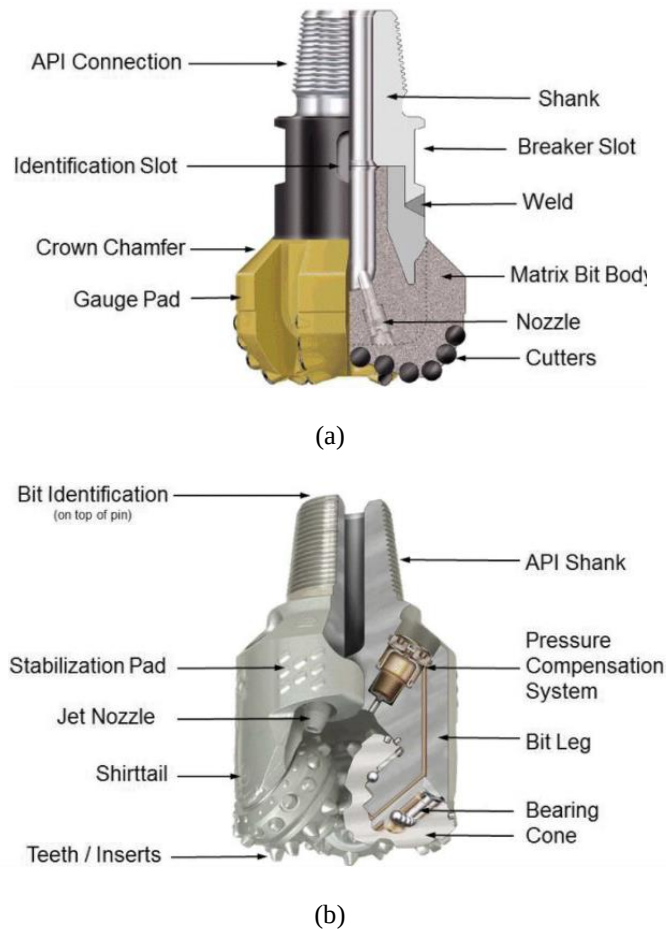
- Drill-bit diameter should be large enough for the casing to slide down freely;
- Air-gap around the casing to allow for the cementing process;
- The larger the diameter of the well, the more expensive the drilling operation.

The study of drill-bits is one important factor in oil well drilling. Drill-bits can be classified into drill-bits without moving parts and with moving parts. Absence of moving parts reduces the chances of equipment failure. According to Thomas (2001), the main drill-bits types without moving parts are steel blades and natural and artificial diamonds, which will be discussed in the following.

- Steel Blades: known as "Fish Tail", these drill-bits were the first to be used in the drilling process. Fish Tail has jets that allow a good cleaning of the blades. However, due to their design, these drill-bits have a very short lifetime;
- Natural diamonds: the material removal process occurs through the grinding effect. These drill-bits are currently used in extremely hard and abrasive rock formations, where other types of drill-bits have difficulty removing material;
- Artificial diamonds: known as Polycrystalline Diamond Compact (PDC) drill-bits, this type of drill-bit removes material through shear, creating a wedge effect. PDC drill-bits revolutionized the O&G industry providing high ROP and a large application range.

In contrast, the drill-bits with moving parts can have one to four cones and consist of two main elements: cutting structure and bearings. The cutting structure is composed of a teeth row mounted on the cone that is interlocking with the teeth rows of adjacent cones when rotating. While the bearings can be produced with rollers and unsealed balls, rollers and sealed balls, or friction bearings. The difference between these bearings types is in the lubrication. Unsealed bearings are self-lubricated and are lubricated by drilling fluid, while sealed bearings have an internal lubrication system. The friction bearings have an internal lubrication system and are covered with noble materials, resulting in higher efficiency and a low failure rate. Figure 14 shows the main differences between PDC and conical roller drill-bits.

Figure 14 - Main differences between: a) PDC drill-bits; b) conical roller drill-bits.



Source: Darwesh, Rasmussen and Al-Ansari (2020).

PDC drill-bits present high performance, however, with technological advances, a hybrid drill-bit was created. The PDC-roller hybrid drill-bit has the characteristics of PDC drill-bits with rolling cutters, as shown in Figure 15. Hybrid drill-bits are efficient in drilling operations, especially in directional drilling and drilling shale and other plastically behaving formations (CIRIMELLO et al., 2018).

Figure 15 - PDC-roller hybrid drill-bit (right) combines roller cone drill-bit (middle) and PDC drill-bit (left).



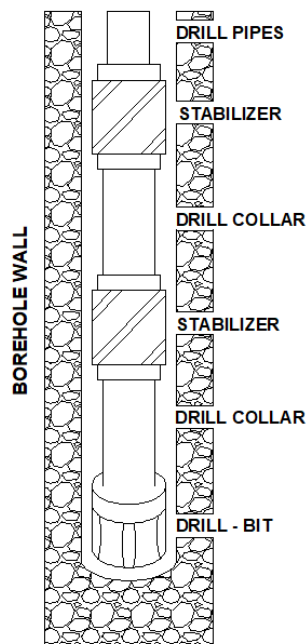
Source: Niu et al. (2019).

The roller cone plays an important function in pre-crushing and pre-fracturing rock in a hybrid drill-bit. The better the effect of pre-crushing and pre-fracturing the rock, the easier it is for PDC cutters to remove the rock and the better the performance that the hybrid drill-bit will achieve (NIU et al., 2018).

In addition to being responsible for exerting TOB and WOB, the drill-string is also responsible for conducting the fluid to the drill-bit. The drilling fluid exits through the drill-bit holes under high pressure, creating jets that reach the rock layer, and in the sequence, the fluid returns to the surface through the annular space, carrying the generated solids and allowing the drilling process to continue (ROCHA; AZEVEDO, 2007).

The drill-string is designed to support the stresses introduced by drilling. During the drilling process, energy in the form of RPM and WOB is transferred to the rocks to promote their rupture and separation. The main components of the drill-string are shown in Figure 16.

Figure 16 - Main components of the drill-string.



Source: Author (2023).

Drill collars have the function of providing weight and rigidity to the drill-string, allowing better control of the well trajectory, while drill pipes are seamless steel tubes treated internally with the application of resins to reduce internal wear and corrosion.

To dimension a drill-string some factors such as mud weight, total depth, internal pressure, maximum expected WOB, traction, and collapse efforts must be known. Drill collars are the first elements to be dimensioned, based on the buckling and number of drill

collars. While for the drill pipes selection, it is necessary to do an analysis of the loads to which it will be subjected.

2.2.7 Blowout preventer

The safety system is composed of equipment to close and control the well. The main safety tool is a set of valves called the Blowout Preventer (BOP). The functions of BOP are to monitor, control and close wells to avoid blowouts, i.e., an uncontrolled liberation of oil and/or gas from a well (LUKIN et al., 2020). Through valve closing, the team can recuperate control of the well and initiate procedures to normalize the situation. For the equipment selection, some operators analyze the parameters described as follows:

- Based on pore pressure: it is assumed that there was a kick, and all fluid was expelled leaving equipment completely full of gas;
- Based on the water depth: the hydrostatic pressure exerted by the water column on the BOP is considered, which would be acting in the opposite direction to the pressure coming from inside the well;
- Based on fracture pressure: the fracture gradient in the shoe acts as an escape valve, i.e., in the occurrence of a kick. If the pressure in the BOP reaches a value greater than the fracture pressure in the shoe, the formation will fracture and the well pressure will decrease;
- Based on casing resistance: if the maximum pressure in the BOP reaches a value greater than the casing working pressure, the casing will rupture, thus reducing the pressure inside the well.

2.2.8 Drilling optimization

The optimization process consists of improving the drilling efficiency through the ideal combination of operational parameters, such as WOB, RPM, TOB, FLOW, among other parameters. Choosing the ideal parameters is a very complex task. An inadequate choice can lead to high values of MSE, in addition to an excessive increase in the vibration of the drill-string, and consequently a drill-bit lifetime reduction.

There is no doubt that ROP is the performance indicator most used during the drilling process. However, drilling too fast into a hard formation can lead to excessive drill-bit wear,

resulting in additional costs and time for a drill-bit replacement (HEGDE et al., 2020). Over time, it was verified that the highest ROP is not always ideal, in fact, it should look for the lowest MSE or a combination of the two parameters (highest ROP and lowest MSE).

A very high MSE is an indication that part of the energy applied to the drill-bit is lost in the generation of excessive vibration, buckling, and drill-bit wear. If for the same ROP, there is a WOB and RPM value that generates a lower MSE, this value must be used. The search for the RPM and WOB value that generates the combination between the lowest MSE and highest ROP is something that can increase the drill-bit lifetime, in addition to substantially reducing the costs of the drilling process (GANDELMAN et al., 2009). This evidences the need to optimize the operating parameters to maintain the ROP and MSE at the desired levels during the drilling process. However, the search for the ideal values of WOB and RPM depends on a reliable model.

2.2.8.1 Rate of Penetration - ROP

In the last decades, several mathematical models were developed to predict the ROP (NASCIMENTO et al., 2015). Maurer (1965) developed a mathematical model for predicting ROP, based on the RPM, WOB, drill-bit diameter, rock strength, and drillability constant. Maurer developed the model based on two observations: An increase in RPM leads to an increase in drill speed; there is only drill-bit penetration after a certain weight value. Young (1969) developed a new model for predicting ROP. According to Young, the Maurer model is unable to predict the non-linear behavior of ROP with RPM. However, though Young's model is adequate to predict the non-linear behavior of ROP with RPM, this model does also not consider important parameters, such as flow rate, overbalance and drill diameter.

As seen, the Maurer and Young model have limitations. These models describe an extremely complex process in a very simplified way. Bourgoyne and Young (1974) proposed a new model to describe the behavior of ROP, much more complex, considering several effects, such as WOB, RPM, depth, differential pressure, pore pressure, formation strength, compaction, drill-bit diameter, drill-bit tooth wear, and bit hydraulic jet impact force.

Due to the several models found in the literature, Nascimento (2016) compared the model of Cunningham (1960), Maurer (1962), and Bourgoyne and Young (1974) using data obtained from Pre-salt drilling. The author evaluated the most adequate model to drill the carbonate formation through simulations using the software Oracle Crystal Ball. Table 1 shows the results obtained by the simulations.

Table 1 - Results obtained by simulation of the different ROP models.

Model	Coefficients	Results	Coefficients boundary	
			Lower	Upper
Cunningham (1960)	a_6	0.28	0.00	1.00
	K	0.47	0.00	10.00
	Relative error	0.58	-	-
	a_5	0.01	0.00	2.00
Maurer (1962)	a_6	0.50	0.00	0.50
	K	2.71	0.00	10.00
	Relative error	0.42	-	-
	a_1	1.90	0.5.	1.90
Bourgoyong e Young (1974)	a_2	0.00	0.00	0.05
	a_3	0.04	0.00	0.09
	a_4	0.00	0.00	0.01
	a_5	0.50	0.50	2.00
	a_6	1.00	0.40	1.00
	a_7	0.30	0.30	1.50
	a_8	0.53	0.30	0.60
	Relative error	0.36	-	-

Source: Nascimento (2016).

Comparing the data shown in Table 1, the Bourgoyne and Young Model (BYM) produce better results and the modeled data fits the field data, with 36.52% of relative error.

2.2.8.2 Mechanical Specific Energy - MSE

MSE is an important parameter to study the efficiency of the rock-breaking process (CHEN et al., 2019; HUANG et al., 2020; LIU et al., 2019). High MSE values usually imply an inappropriate rock-breaking process, increase the cost of the drilling process, and can indicate undesirable effects such as vibrations, high drill-bit wear, and high temperatures (CHENG et al., 2018). The combination of these effects can lead to drill-bit failure and consequently, additional time to change equipment (TUNKIEL; SUI; WIKTORSKI, 2021). While, a smaller MSE value indicates an efficient rock-breaking process, reducing operating time and cost (CHEN et al., 2020).

Several authors have been presenting different methods for analyzing MSE in the last decades. These methods aim at solving specific issues during the drilling process. According to Chen et al. (2014), the ideal MSE model should have the following main properties:

- The minimum MSE value should be approximately equal to the Confined Compressive Strength (CCS) value of the rock during the drilling;
- The parameters of the model must be easily measured and calculated;

- The model should be adequate for different types of drill-bits and wells.

The first equation for calculating MSE was presented by Teale (1965) for a rotary system based on experimental results, as represented by equation (1).

$$MSE = \frac{WOB}{A_b} + \frac{120 \cdot \pi \cdot RPM \cdot TOB}{A_b \cdot ROP} \quad (1)$$

The equation presented by Teale (1965) presents a disadvantage, it requires TOB measurement which is not always available during the drilling process (ABBAS, 2018). During the drilling process, the most commonly measured properties are ROP, WOB, and RPM. Consequently, many authors have developed methods for calculating MSE without accounting for TOB values (PESSIER; FEAR, 1992). Considering the problem presented, Pessier and Fear (1992) introduced the Bit-Specific Coefficient of Sliding Friction (μ_b) to obtain the TOB value, as shown in equation (2).

$$TOB = \mu_b \frac{D_B \cdot WOB}{36} \quad (2)$$

Substituting the TOB applied on the drill-bit by the μ_b , equation (3) is obtained.

$$MSE = WOB \left(\frac{1}{A_b} + \frac{13.33 \cdot \mu_b \cdot RPM}{D_b \cdot ROP} \right) \quad (3)$$

Later, Dupriest and Koederitz (2005) adjusted the equation originally introduced by Teale (1965). For this, the researchers included the Drilling Efficiency Factor (EFF_M) as shown in equation (4).

$$MSE_{adj} = EFF_M \cdot MSE \quad (4)$$

For perfect efficiency during the drilling process, the MSE would be equal to the CCS of rock (DUPRIEST; KOEDERITZ, 2005). However, drilling processes are typically only 30-40% efficient at peak performance (PESSIER; FEAR, 1992). This means that MSE values based on field data were three times higher than rock CCS. Thus, Dupriest and Koederitz (2005) suggested considering the EFF_M of 35%, as represented by equation (5).

$$MSE_{adj} = 0.35 \cdot \left(\frac{WOB}{A_b} + \frac{120 \cdot \pi \cdot RPM \cdot TOB}{A_b \cdot ROP} \right) \quad (5)$$

WOB and TOB, in horizontal wells, are greatly inflated by well friction (CHEN et al., 2014). Due to the fact presented, Chen et al. (2014) created a new model for the TOB and downhole weight-on-bit (WOB_b). Equations (6) and (7) present the new models for WOB_b and TOB, modified by wall friction coefficient and bottom hole inclination.

$$WOB_b = WOB \cdot e^{-\mu_s \gamma_b} \quad (6)$$

$$TOB = \frac{\mu_b \cdot WOB \cdot D_b}{3} = \frac{\mu_b \cdot WOB \cdot e^{-\mu_s \gamma_b} \cdot D_b}{3} \quad (7)$$

Substituting equations (6) and (7) in the equation presented by Teale (1965) and introducing the Mechanical Efficiency (E_m), a new MSE equation is obtained to horizontal well, as shown in equation (8):

$$MSE = E_m \cdot WOB_b \cdot \left(\frac{1}{A_b} + \frac{13.33 \cdot \mu_b \cdot RPM}{D_b \cdot ROP} \right) \quad (8)$$

Drill-bits cutters suffer continuous wear due to the friction with rocks, consequently, causing a reduction in ROP (AL-SUDANI, 2017). Many researchers searched for the ideal way to detect the wear of drill-bits and predict their lifetime (ABBAS, 2018). An analytical model of interaction between rock and drill-bit was developed by Al-Sudani (2017), as shown in equation (9).

$$MSE_{new} = \frac{\sqrt{\frac{WOB (120 \cdot \pi \cdot RPM)^2 \cdot TOB}{g_c \left(\frac{D_b}{12} \right)^2}}}{ROP} \quad (9)$$

Through the analytical model, it is possible to analyze the required and dissipated MSE in real-time, and account for the wear of the drill-bit. The analytical model presented was developed through the variation of the MSE required as a function of the drill-bit wear, and the drill-bit wear as a function of the MSE generated (AL-SUDANI, 2017).

In recent years with technological progress, the Positive Displacement Engine (PDM) is being used in drilling hard formations (CHEN et al., 2016). PDM converts hydraulic energy

from the mud flow into mechanical rotary power (SAMUEL; MISKA; VOLK, 1997; MOTAHHARI et al., 2009). In this way, Chen et al. (2016) developed a new MSE model for the PDM, as shown in equation (10).

$$MSE = E_m \left(WOB \cdot e^{-\mu_s \gamma_b} \left(\frac{1}{A_b} + \frac{13.33 \cdot \mu_b \cdot RPM_s}{D_b \cdot ROP} \right) + \frac{1155.2 \cdot \eta \cdot \Delta P_m \cdot FLOW}{A_b \cdot ROP} \right) \quad (10)$$

Some researchers went further and introduced the term “hydraulic energy”. The energy required to remove a unit volume of rock comes primarily from the WOB, TOB and hydraulic force exerted by the drilling fluid on the formation (MOHAN; ADIL; SAMUEL, 2009, 2015).

Thus, the term Hydro-Mechanical Specific Energy (HSME) was created, which includes mechanical energy and hydraulic energy. The hydraulic term included in the MSE correlation is key to correctly determining the amount of energy used during the drilling process, as well as identifying inefficient drilling conditions (MOHAN; ADIL; SAMUEL, 2009, 2015). For authors the HSME can be defined through equation (11) as follows:

$$HMSE = \frac{WOB_e}{A_b} + \frac{120 \cdot \pi \cdot RPM \cdot TOB + 1154 \cdot n \cdot \Delta P_b \cdot FLOW}{A_b \cdot ROP} \quad (11)$$

2.2.8.3 Multiple Linear Regression Model

Multiple Linear Regression (MLR) models are widely used to analyze the relation between a response and several input variables (CRIBARI-NETO; LIMA, 2010; RASYIDAH et al., 2023). The model form of multiple regression is shown in equation (12) (KESHAVARZ MORAVEJI; NADERI, 2016).

$$Y = \beta_0 + \sum_{j=1}^k \beta_j X_j + \sum_{j=1}^k \beta_{jj} X_j^2 + \sum_{i < j}^{k-1} \sum_{j=2}^k \beta_{ij} X_i X_j \quad (12)$$

According to Keshavarz Moraveji and Naderi (2016), the hypotheses to test the significance are:

Null hypothesis: $\beta_i = 0$ for X_i

Alternate hypothesis: $\beta_i \neq 0$ for X_i

(13)

A P-value greater than the significance level indicates that coefficient β_i is zero, i.e., X_i can be removed from the model (KESHAVARZ MORAVEJI; NADERI, 2016). Moreover, the statistical analyses have uncertainty, called standard error, due to sampling variability (MANSOURNIA et al., 2021). If the residuals have Heteroscedasticity and Autocorrelation Consistent (HAC), then the model will lead to incorrect conclusions (HARTIGAN, 2018).

A solution is to use "robust standard errors", which are used to correct standard errors and avoid the effects of heteroscedasticity in linear regression (KING; ROBERTS, 2015; MANSOURNIA et al., 2021). In literature, several Heteroscedasticity Consistent Covariance Matrix Estimators (HCCME) were developed, including HC0 estimator and its variants, such as HC1, HC2, HC3 (ASLAM; RIAZ; ALTAF, 2013; LI et al., 2016). HC1 uses a global degrees-of-freedom adjustment, HC2 is constructed using standardized ordinary least squares residuals, and HC3 which is an approximation to the jackknife estimator (ROMANO; WOLF, 2017; HARTIGAN, 2018).

2.2.8.4 Multi-Objective Optimization

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 room of drilling mechanic parameters (GANDELMAN, 2012; HEGDE; GRAY, 2018), accounting for the optimum ROP and MSE concomitantly. 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 Total Desirability (D) developed by Derrig and Suich (2018). This method is based on three response types: Nominal-The-Best (NTB), Larger-The-Better (LTB), and Smaller-The-Better answers (STB).

- Nominal-The-Best (NTB): this function is used when the value of the response is expected to achieve a particular target value. The NTB function is defined as per equation (14).

$$d = \begin{cases} \left[\frac{\hat{y} - L}{T - L} \right]^S & L \leq \hat{y} \leq T \\ \left[\frac{\hat{y} - U}{T - U} \right]^R & T \leq \hat{y} \leq U \\ 0 & \text{se } \hat{y} < L \text{ ou } \hat{y} > U \end{cases} \quad (14)$$

- Larger-The-Better (LTB): this function is used when the value of the response is expected to achieve the maximum value of the function. The LTB function is defined as per equation (15).

$$d = \begin{cases} 0 & \hat{y} < L \\ \left[\frac{\hat{y} - L}{U - L} \right]^R & L \leq \hat{y} \leq U \\ 1 & \hat{y} > U \end{cases} \quad (15)$$

- Smaller-The-Better (STB): this function is used when the value of the response is expected to achieve the minimum value of the function. The STB function is defined as per equation (16).

$$d = \begin{cases} 0 & \hat{y} < U \\ \left[\frac{\hat{y} - U}{L - U} \right]^R & L \leq \hat{y} \leq U \\ 1 & \hat{y} < L \end{cases} \quad (16)$$

In the sequence, the optimization of the individual responses is performed by the global function, as represented per equation (17).

$$D = (d_1 \times d_2 \times d_3 \times \dots \times d_n)^{\left(\frac{1}{p}\right)} \quad (17)$$

Where: R and S are 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.

2.2.9 Well completion

The well design is finished with the completion of the drilling and completion program. The completion process refers to the set of operations intended to equip the well and leave it in condition to operate safely and economically after the end of the drilling process.

There are three different types of completion, as to the wellhead position, production casing, and the number of explored areas:

- Wellhead position: on land, the wellhead is positioned on the surface. At sea, in non-deep water, it is also possible to install the wellhead on the surface. Even in non-deep water, the wellhead can be installed on the seabed, complete with a Wet Christmas Tree (ANN);
- Production casing: the completion can be created as an open hole, perforated liner, or perforated casing. Open-hole completion is only used in very well-consolidated formations. It has the advantages of a larger area open to the flow and reduced casing costs. Liner completion has advantages related to the support of the walls in front of the producing zone and the disadvantage of the additional cost. The perforated liner has the advantage of lower casing cost and the disadvantage of changing the diameter inside the well. While perforated casing, which is the most used today, has as main advantages and disadvantages, the production selectivity in different intervals of interest and the additional casing cost, respectively;
- The number of zones explored: the exploration of a single zone enables to the production of hydrocarbons in a controlled and independent way. The exploration of multiple zones allows to the production of two or more different zones, through one or more production columns.

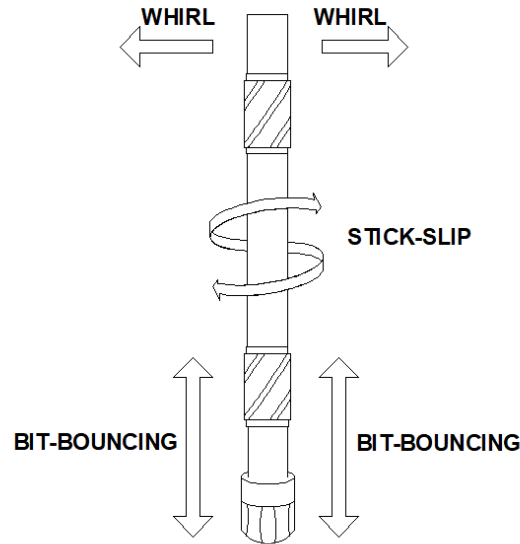
2.4 VIBRATION MODELING

The objective of vibration analysis is to avoid the input parameter values not causing excessive vibrations when implemented. According to Christoforou and Yigit (2003), vibrations can be classified into three types:

- Axial vibration: characterized by bouncing in the drill-bit, this vibration is produced in the vertical direction of the drill-string;
- Lateral vibration: also known as whirl, this vibration is produced when the center of mass of the drill-string is displaced from the rotation axis;
- Torsional vibration: produced when the rotary speed at the surface and downhole are different, causing movements called stick-slip.

The lateral and torsional vibrations cause excessive drill-bit wear, poor drilling rates and premature tool failures (HONG; GIRSANG; DHUPIA, 2016). Each vibration type appears at different times and frequencies, therefore, can be analyzed separately, as shown in Figure 17.

Figure 17 - Vibrations in the drill-string.



Source: Author (2023).

The stick-slip vibrations are characterized by the absorption (i.e., stick) and release (i.e., slip) of energy as a function of the resisting forces (HONG; GIRSANG; DHUPIA, 2016). The energy release can vary the rotary speed of the drill-string from zero to six times (JANSEN; VAN DEN STEEN, 1995). Equation (18) shows a metric used to represent the effect of stick-slip vibrations, called the stick-slip index (SSI) (ERTAŞ et al., 2014; LINES; MAULDIN; HILL; AIELLO, 2014; HEGDE; MILLWATER; GRAY, 2019).

$$SSI = \frac{Max (bit \text{ RPM}) - Min (bit \text{ RPM})}{Average (bit \text{ RPM})} \quad (18)$$

Where a value of SSI equals 1 represents a full stick-slip, i.e., the drill-bit is momentarily stationary (ERTAŞ et al., 2014; HEGDE; MILLWATER; GRAY, 2019).

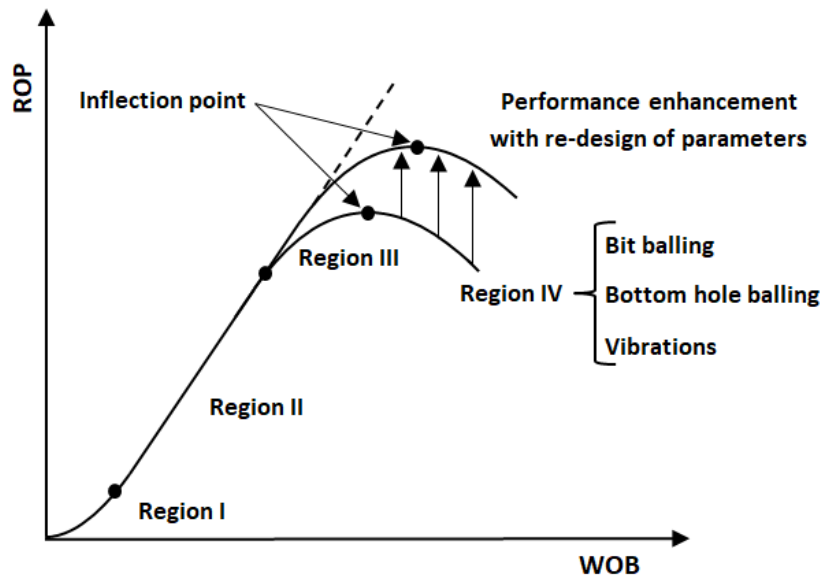
2.5 PRE-OPERATIONAL TEST

One of the main problems during the drilling activities is the excess of hardness and abrasiveness found in Pre-salt carbonates. These characteristics can lead to early drill-bit teeth-cutters breakage/dullness/wear (NASCIMENTO et al., 2019). All these events affect the drilling efficiency in Pre-salt operations. Drilling efficiency is a consequence of the Total Non-Productive Time (NPT) (RAMBA et al., 2021). Usually, NPT represents one-third of the total rig operational cost (WEBB et al., 2016). Statistical analysis in the Gulf of Mexico showed that over 10 years, loss of circulation and kicks and well instabilities accounted for 12 and 18% of NPT, respectively (REHM et al., 2013). A similar analysis showed that loss circulation is responsible for increasing drilling costs by 70 to 100 [USD] per foot (MAGZOUN et al., 2020). In this context, there is still room for improvements in 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 exploration/exploitation of other natural resources (NASCIMENTO et al., 2019).

To overcome these obstacles, a new methodology must be developed to obtain the ideal drilling parameters. The drillability of the formations can be estimated through pre-operational tests, such as the drill-rate test (DRT) and drill-off test (DOT). DRT and DOT methodology were developed in the 1950s to reduce the drilling time by determining ideal parameters (RPM and WOB) for drilling the specific formation. Through DRT, the following questions can be addressed: (a) how far increasing the WOB value would be effective and efficient? (b) how far would this decision lead to unnecessary machinery overload? RPM and WOB are the main parameters in the drilling process and should be analyzed in real-time (RAMBA et al., 2021).

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 of continuously increasing the WOB, maintaining approximately fixed RPM values (which varies for another test run always for specific given fixed RPM) (SOUTO; NASCIMENTO, 2016). Figure 18 shows the drill-rate test.

Figure 18 - Drill-rate test curve.



Source: Adapted from Nascimento (2016).

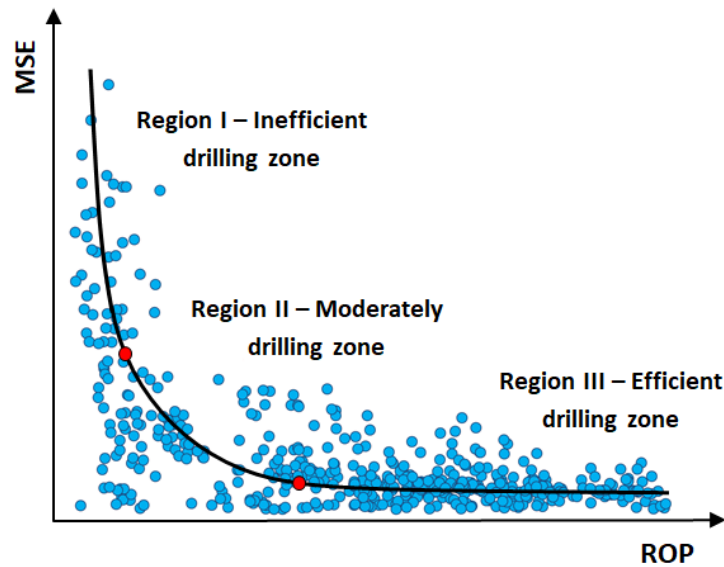
The curve has three well-defined regions:

- Region I: for starting the drilling process is necessary a disproportionate increase in WOB, i.e., there is only drill-bit penetration after a determined WOB value;
- Region II: defined by a constant slope line, with the highest possible efficiency. The increase in the WOB in this region results in a proportional increase in the ROP;
- Region III: defined as the region at which ROP stops responding linearly with an increase in WOB. In this region is found the inflection point, i.e., the maximum ROP value for determining the combination between WOB and RPM. From the inflection point starts region four;
- Region IV: characterized by processes that restrict energy transfer, cause vibrations and reduce process efficiency. The restricted energy transfer occurs due to rock accumulation in the drill-bit and can be described by terms such as "bit balling" and "bottom hole balling" (DUPRIEST; KOEDERITZ, 2005). While the vibrations, divided into whirl (lateral), stick-slip (torsional), and bit bounce (axial), cause drill-bit and downhole tool failures, consequently, increasing the cost and time of the drilling process.

The optimization of the drilling process does not consist simply in obtaining the parameters that provide the highest ROP. In fact, one must search for parameters that allow drilling a phase in the shortest time. The use of the drill-rate test curve together with the concept of the MSE allows for obtaining parameters that help in the optimization process. Not

only, maximizing the ROP, but looking for the combination between the highest ROP and the lowest MSE, through the combination of ideal operating conditions (WOB and RPM). Figure 19 shows the relation between the MSE versus ROP plot.

Figure 19 - MSE versus ROP plot with the indication of efficient/inefficient regions.



Source: Author (2023).

Figure 19 is divided in three regions, namely: region I (inefficient drilling zone), region II (moderately drilling zone), and region III (efficient drilling zone). The maximum efficiency in the drilling process is obtained in region III. In this region, the values of ROP are high, while the MSE is maintained at low values.

3 METHODOLOGY

3.1 DATASET ACQUISITION

A field dataset from a real Pre-salt operation was used for the analyses performed throughout the presented Dissertation. The dataset represents essentially the reservoir layer (Pre-salt), a carbonate hard rock interval drilled in the south Atlantic Ocean, containing different, interesting, and important information. Several different mechanical parameters such as depth, rate of penetration (ROP), drill-string rotary speed (RPM), weight-on-bit (WOB), torque-on-bit (TOB), flow-rate (FLOW), among others, were taken into account. Different analyses were performed, where the main in use covers 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". The dataset provided are confidential, were made available through previously developed theses and dissertations at the São Paulo State University (UNESP), and can not be presented in full details (Appendix C).

3.2 OUTLIER ELIMINATION

The main challenges of data analysis are associated with data quality. The common problems are outliers, missing data and faulty measurements (HASSAN; ELKATATNY; AL-MAJED, 2020; ENCINAS; TUNKIEL; SUI, 2022). The identification and remotion of outliers is a necessary step of data analysis to avoid erroneous conclusions (SCHWERTMAN; DE SILVA, 2007; ZHANG et al., 2020). A widely used statistical outlier identification method is Tukey's box plot method (TUKEY, 1977).

The box plot method is a graphical technique that calculates data distribution through of smallest normal observation (f_1), largest normal observation (f_3), lower quartile value (H_L), and upper quartile value (H_U). The statistical method presented by Tukey (1977) is based on obtaining limits, called “inner fences” and “outer fences” and uses the estimated interquartile range (IQR), denominated H-spread (d_H), such as shown in the equation (19):

$$d_H = H_U - H_L \quad (19)$$

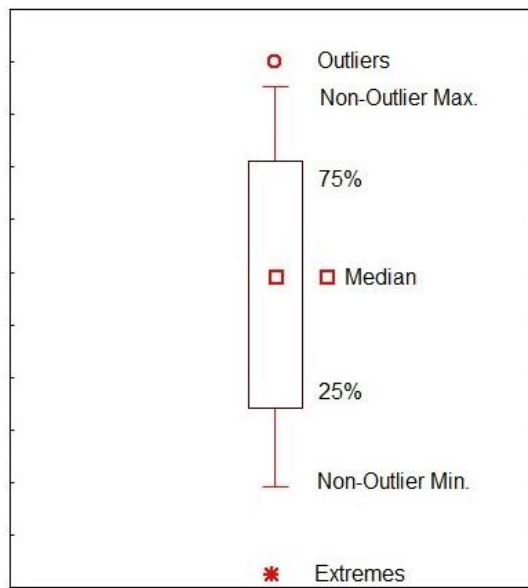
To obtain the value of “inner fences” and “outer fences” is used the constant $k=1.5$ for the “inner fences” and $k=3$ for the “outer fences”, such as shown in the equations (20) and (21).

$$f1 = H_L - k \cdot d_H \quad (20)$$

$$f3 = H_U + k \cdot d_H \quad (21)$$

Any values found beyond the lower and upper limits are outliers, however, outliers can be considered extreme if beyond the outer fence (BARBATO et al., 2011). Figure 20 shows Tukey's box plot method.

Figure 20 - Tukey's box plot method.



Source: Author (2023).

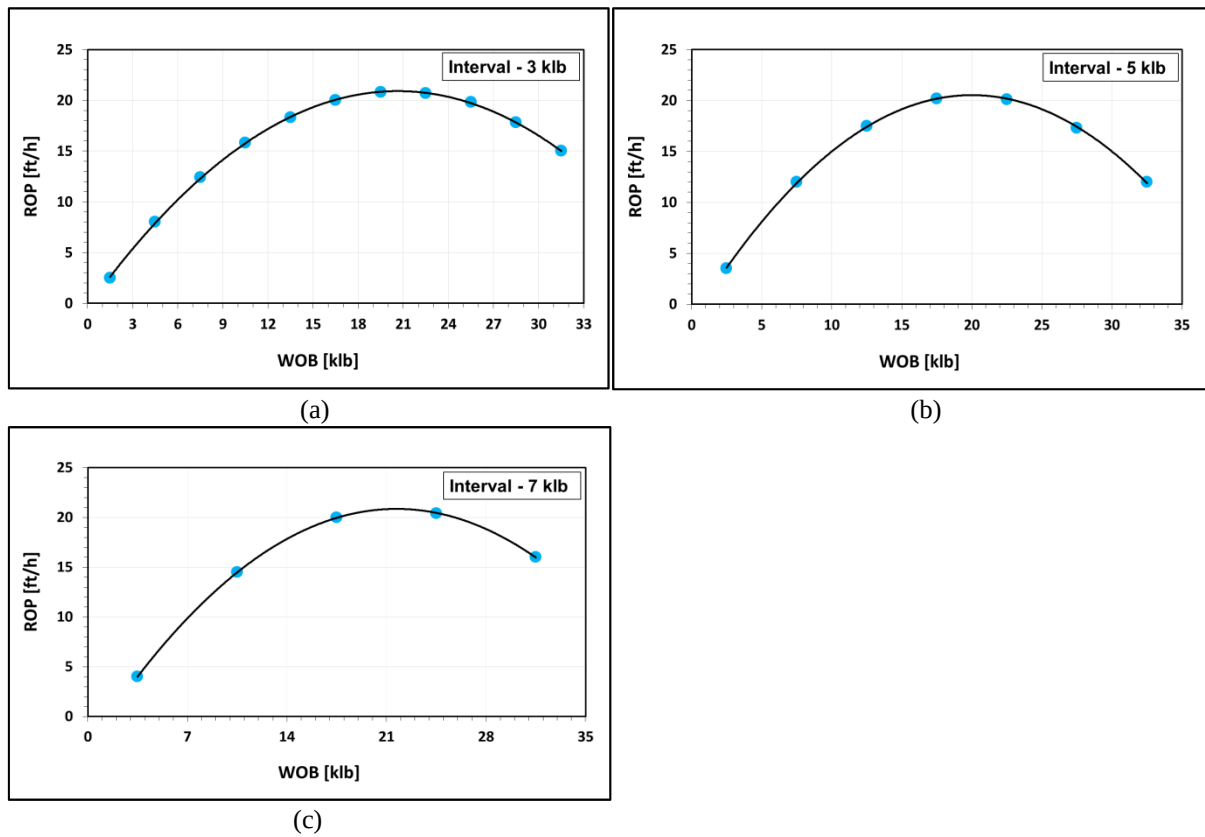
3.3 DRILL-RATE TEST

The steps for the construction of drill-rate test curves from a drilling dataset are as follows: (i) dataset was initially separated by different RPM values using an interval of 10 rev/min. Usually, the petroleum wells are drilled using drill-string rotary speed from 60 to 160 [rev/min], depending on the specificities of the drilling operations and the provided drilling programs; (ii) to each interval of RPM, the mean value of the WOB, ROP, and MSE parameters were performed with respect to WOB for intervals of 3, 5, and 7 [klb]; (iii) plot a

second-degree polynomial curve for ROP vs. WOB, and MSE vs. WOB for different RPM intervals.

The analyses considering WOB intervals of 3, 5, and 7 [klb] have the goal to investigate the smallest amount of tests for a given RPM would allow obtaining a consistent drill-rate test in a fast and agile way due to the high daily cost of the drilling rig. Figure 21 shows an example of the drill-rate test to intervals of 3, 5, and 7 [klb].

Figure 21 - Example of the drill-rate test to intervals of: (a) 3 [klb]; (b) 5 [klb]; (c) 7 [klb].



Source: Author (2023).

Figure 21 shows that using a WOB interval of 3 [klb] is necessary to perform eight tests on average (represented by blue points) to obtain the quadratic curve and founder point. To the intervals of 5 and 7 [klb] are necessary five and four tests on average, respectively. However, must be investigated if the smallest number of tests provides a good parameter fit when compared with other tests.

It is known from the industry, that these tests are neglected due to the false non-advantage impression because it demands considerable time to be performed, a wrong impression when comparing the operational time gained with the time spent in order to safely and accurately perform such a pre-operational drilling test.

3.4 MULTI-OBJECTIVE OPTIMIZATION

The objective is to obtain a multi-objective optimization able to combine the maximum ROP and the minimum MSE, concomitantly. ROP maximum response will be based on equation (15), while the MSE will be minimized according to equation (16), both presented in section 2.2.8.4. In the sequence, equation (17) is used to obtain the desirability value. A multi-objective optimization is performed using the software Microsoft Excel version 14.072.685.000 as a base, as shown in Figure 22. Excel is simple, user-friendly, highly versatile, and one of the most widely used mathematical software in the world. In addition, Microsoft Excel is a useful tool for optimization problems and demonstrates that it is not necessary to use specific statistical software.

Figure 22 - Multi-objective optimization.

MULTI-OBJECTIVE OPTIMIZATION

ROP	COEFFICIENTS
Intersection	-9.152
WOB	2.528
WOB²	-0.056

DECISION VARIABLE	
WOB [klb]	21.17

	LOWER LIMIT	UPPER LIMIT
ROP [ft/h]	2.80	20.57
MSE [kpsi]	59.52	978.28
WOB [klb]	7.55	41.33

MSE	COEFFICIENTS
Intersection	1026.256
WOB	-89.495
WOB²	2.114

FUNCTION	VALUES
ROP [ft/h]	19.06
MSE [kpsi]	78.85
DESIRABILITY - ROP	0.92
DESIRABILITY - MSE	0.98
TOTAL DESIRABILITY	0.92

LOOP
1
1.00
0.00

Optimization

WEIGHT - ROP	WEIGHT - MSE	WOB [klb]	DESIRABILITY - ROP	DESIRABILITY - MSE	ROP [ft/h]	MSE [kpsi]	TOTAL DESIRABILITY
1.00	0.00	22.393	0.920	0.976	19.147	81.997	0.920
0.90	0.10	22.307	0.920	0.976	19.146	81.568	0.925
0.80	0.20	22.215	0.920	0.976	19.145	81.146	0.931
0.70	0.30	22.117	0.920	0.977	19.143	80.734	0.936
0.60	0.40	22.011	0.919	0.977	19.139	80.337	0.942
0.50	0.50	21.898	0.919	0.978	19.133	79.963	0.948
0.40	0.60	21.776	0.919	0.978	19.125	79.620	0.954
0.30	0.70	21.644	0.918	0.978	19.115	79.320	0.960
0.20	0.80	21.501	0.917	0.979	19.102	79.077	0.966
0.10	0.90	21.344	0.916	0.979	19.085	78.912	0.972
0.00	1.00	21.172	0.915	0.979	19.063	78.849	0.979
		21.172	0.915	0.979	19.063	78.849	0.915

Source: Author (2023).

The Generalized Reduced Gradient (GRG) nonlinear solver method was used in this analysis, in order to obtain the ideal combination between the maximum ROP and the minimum MSE. In addition, to obtain the optimal points is used the option "use multiple starts". Figure 23 shows the part of the computational coding used to automate the different scenarios under analysis.

Figure 23 - Code used to automate the different scenarios.

```

Private Sub CommandButton1_Click()
    inicio = Now
    For n = 1 To 11
        Range("AA17") = n 'LOOP
        solversolve userfinish:=True
        Range("X" & n + 24 & ":AC" & n + 24).Value = Range("X36:AC36").Value
    Next n
End Sub

```

Source: Author (2023).

The optimization process was realized using different values of weights for the response variables, allowing the operator to choose the best scenario for the current drilling process. The different values of weight used in the optimization are shown in Table 2.

Table 2 - Values of weights used in the optimization process.

Scenario	Weight - ROP	Weight - MSE
01	1.00	0.00
02	0.90	0.10
03	0.80	0.20
04	0.70	0.30
05	0.60	0.40
06	0.50	0.50
07	0.40	0.60
08	0.30	0.70
09	0.20	0.80
10	0.10	0.90
11	0.00	1.00

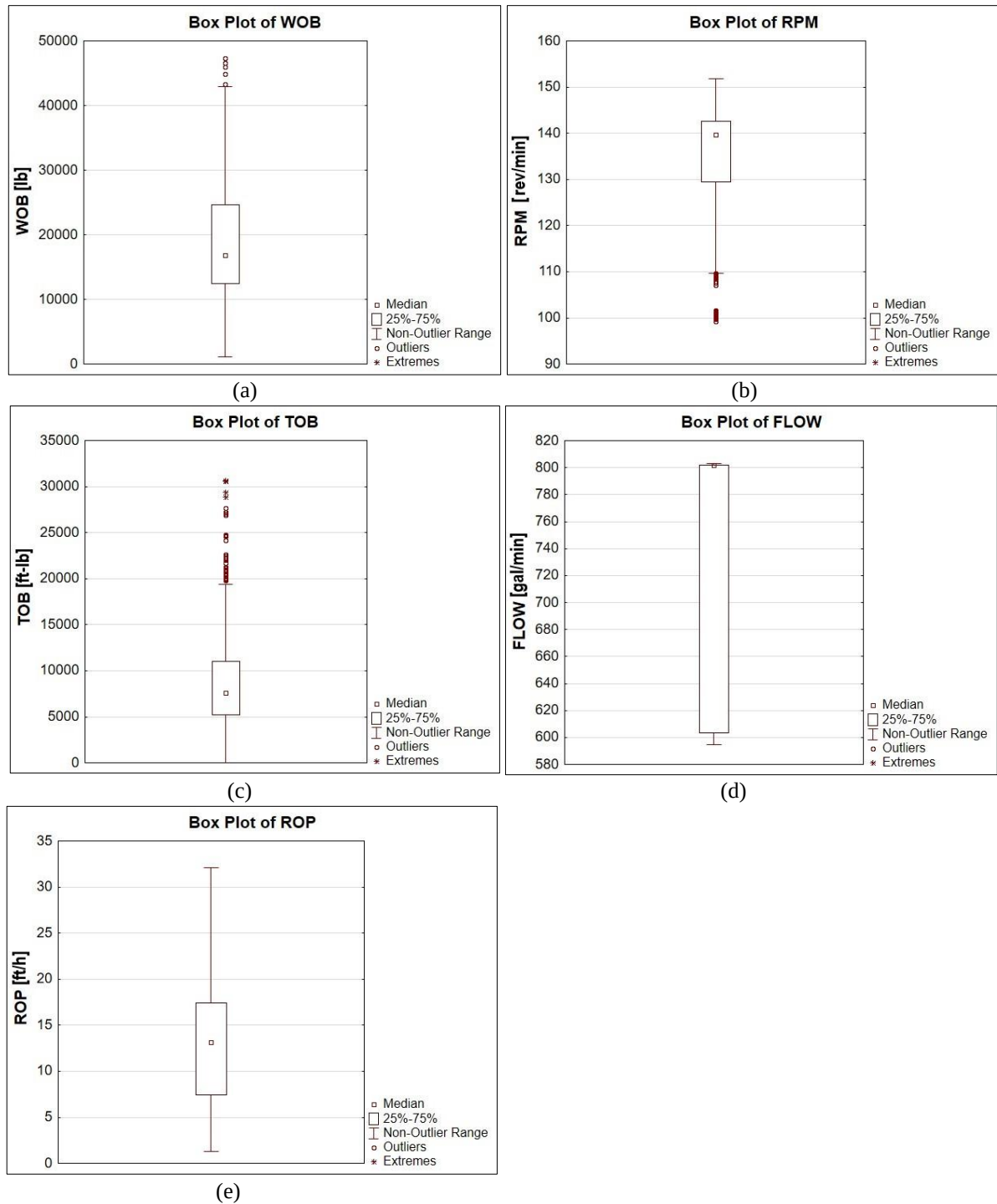
Source: Author (2023).

4 RESULTS AND DISCUSSION

4.1 OUTLIER ELIMINATION

Tukey's box plot method was used to identify the outliers, the result is shown in Figure 24.

Figure 24 - Tukey's box plot method: a) WOB; b) RPM; c) TOB; d) FLOW; e) ROP.



Source: Author (2023).

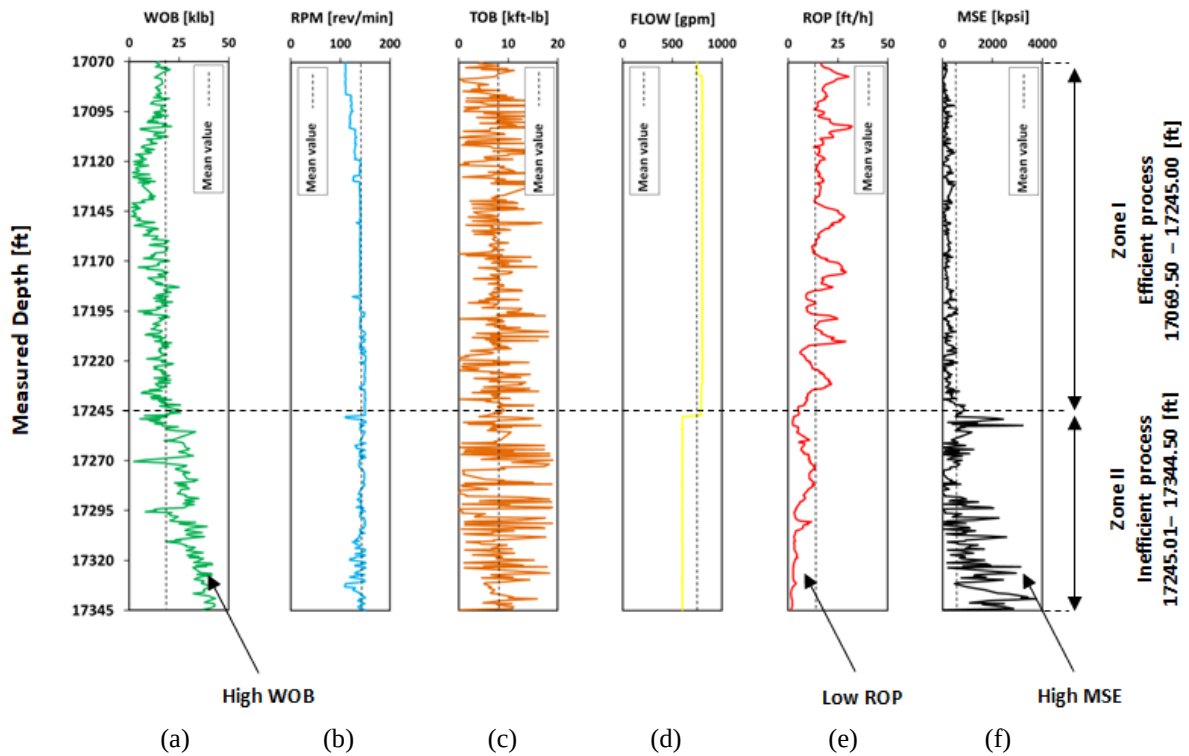
The outlier removed process was applied to all variables analyzed, however, only RPM, WOB, and TOB presented outliers. As shown in Figure 24-a, the WOB's non-outlier range varies between 1090.98 (minimum value) and 43310.32 [lb] (maximum value). The non-outlier range of the RPM varies between 109.36 (minimum value) and 160.68 [rev/min] (maximum value) (Figure 24-b). While the non-outlier range of TOB varies between 7.69 (minimum value) and 19004.22 [ft-lb] (maximum value) (Figure 24-c).

4.2 TRADITIONAL METHOD OF ANALYSIS

4.2.1 2D Analysis

The traditional method of analysis consists in representing the drilling mechanic parameters data through 2D plots as a function of depth. Figure 25 shows the input variables (WOB, RPM, TOB and FLOW) and response variables (ROP and MSE) of the drilling process analyzed in this research.

Figure 25 - Input and response variables.



Source: Author (2023).

As shown in Figure 25-a, 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) (Figure 25-b). The mean value of the TOB is 7.62 [kft-lb] with a range that varies between 0.01 [kft-lb] (minimum value) and 19.00 [kft-lb] (maximum value) (Figure 25-c). The mean value of the flow-rate is 735.05 [gal/min], with a range that varies between 594.86 [gal/min] (minimum value) and 803.32 [gal/min] (maximum value) (Figure 25-d).

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/hr] (Figure 25-e). MSE value was calculated through equation (1) (Teale's model) shown in section 2.2.8.2. 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) (Figure 25-f). The summary of statistical information is described in Table 3, and the distribution of the dataset can be seen in Figure 34 (Appendix A).

Table 3 – Summary of statistical information.

Factor	Coded Factor	Minimum Value	Mean Value	Maximum Value
WOB [klb]	X ₁	1.09	18.27	43.31
RPM [rev/min]	X ₂	109.36	137.99	151.77
TOB [kft-lb]	X ₃	0.01	7.62	19.00
FLOW [gpm]	X ₄	594.86	735.05	803.32
ROP [ft/h]	Y ₁	1.29	13.00	32.12
MSE [kpsi]	Y ₂	0.61	462.01	3750.44

Source: Author (2023).

Figure 25 can be divided into two zones. Zone I from 17,069.50 to 17,245.00 [ft] is characterized by an efficient process, and zone II from 17,069.01 to 17,344.50 [ft] is characterized by an inefficient process due to the high value of WOB, i.e., probably the drilling process occurs in region IV as per Figure 18.

Zone I shows a stable trend, indicating that the MSE of the drilling process at this time is relatively low, while ROP reaches considerably high values. In this zone, the mean value of ROP is 16.67 [ft/h], which is relatively higher compared to observed in zone II. The mean value of MSE and WOB in the zone I are 227.87 [kpsi] and 13.30 [klb], which is relatively lower than the value observed in zone II.

However, in zone II, 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 ROP is 3.42 [ft/h], which is relatively low. MSE reaches a mean value of 941.24 [kpsi], which is extremely high compared com MSE's mean value of 227.87 [kpsi] (zone I). This increasing

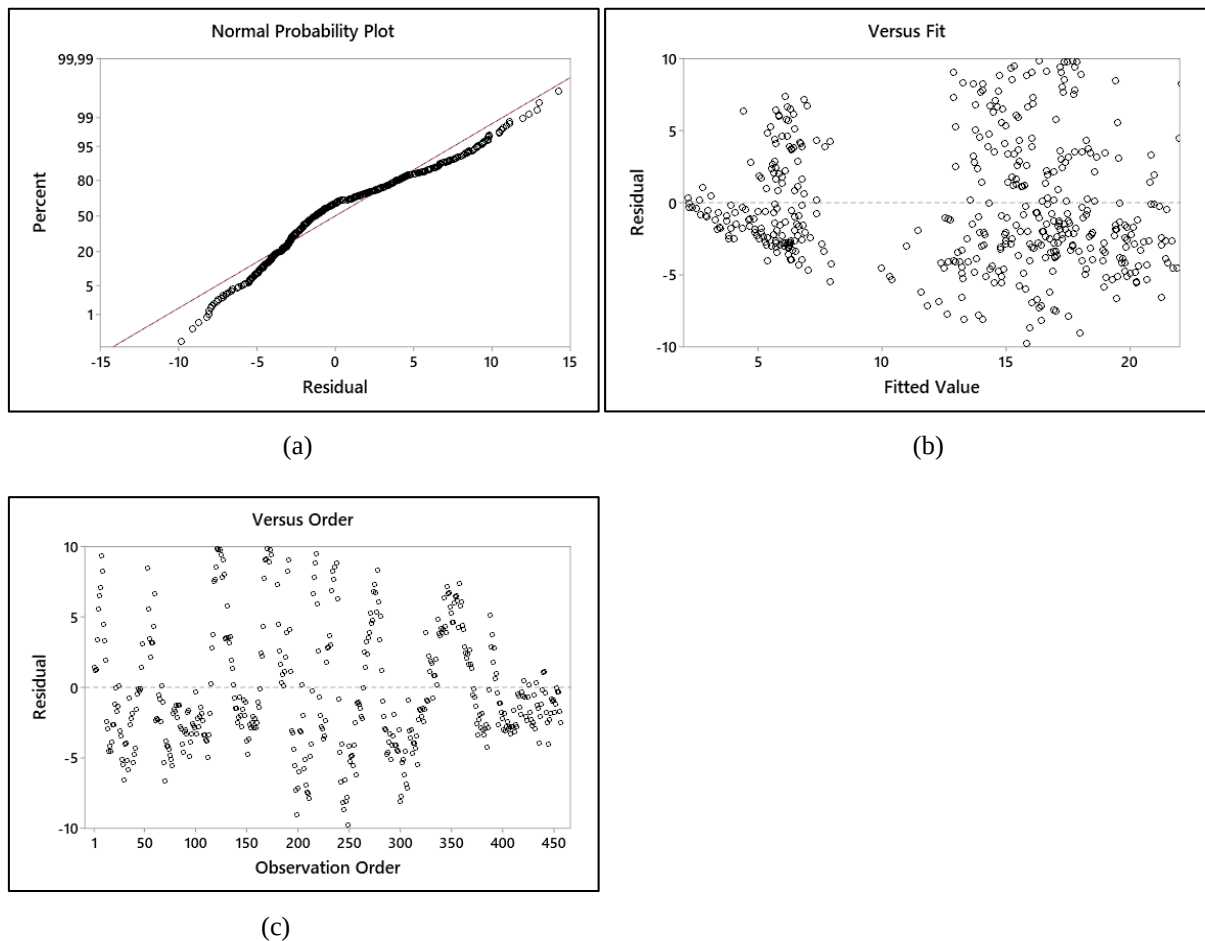
trend occurs due to the high value of WOB, which, in this case, reflects a low ROP, and most probably indicates an operation beyond the foundering point as per Figure 18. WOB exceeds the mean value of 18.27 [klb] and reaches the maximum value of 42.88 [klb]. Moreover, in this zone occurs the decrease in flow-rate value, which reaches the minimum value of 594.86 [gal/min]. The use of these drilling mechanic parameters causes undesirable effects that will lead to vibrations, drill-bit wear, and consequently an increase in time and cost.

4.2.2 Response surface methodology

4.2.2.1 Analysis of ROP

The first step in linear regression is to analyze the statistical performance of the model. In this research, residual plots and coefficients of determination (R^2) were used to evaluate the prediction capability of the model. Figure 26 presents the residual plots of regression.

Figure 26 - Residual plots: a) normal probability plot; b) versus fit; c) versus order.



Source: Author (2023).

Visual analysis of residual plots does not indicate a clear violation of regression model supposition for the fitted data. The model presents a good fit that can be verified through the coefficient of determination (R^2) and adjusted coefficient of determination (R_{adj}^2) of 90.51 and 90.34%, respectively. In addition, a simple hypothesis test technique is applied to detect heteroscedasticity. Heteroscedasticity means a situation in which the variance of the dependent variables varies across the analyzed data (ZOLNA et al., 2016). To detect the existence of heteroscedasticity, the test proposed by Breusch-Pagan (1980) was used, which the null hypothesis is that the variance of the residuals is constant (COSTAGLIOLA et al., 2008).

However, the Breusch-Pagan test revealed a violation of the homoscedasticity assumption, i.e., the p-value of the test is lower than 0.05. Thus, the null hypothesis of homoscedasticity of the residuals can be rejected. To solve this problem, the model was re-estimated using the method to obtain heteroscedasticity-consistent standard errors (variant HC2). Table 4 shows the estimates of the significant effects of these factors on the ROP using a 5% level of significance. For comparison purposes, the model was re-estimated using the HC0, HC1, and HC3 variants as can be seen in Tables 13, 14, and 15, respectively (Appendix B).

Table 4 – Effect of factors on ROP.

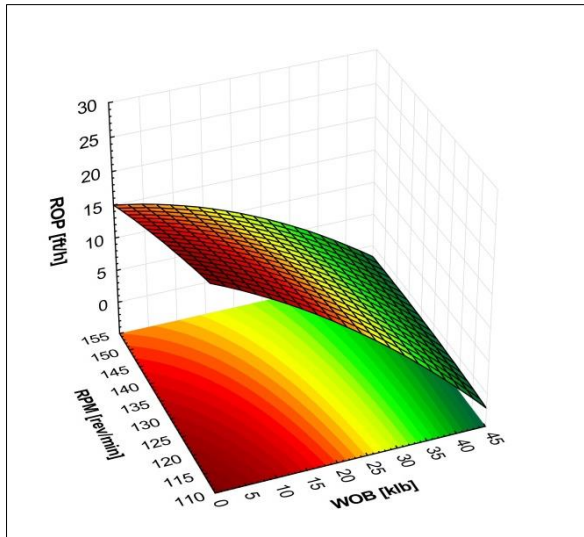
Factor	Effect	Standard deviation	T-value	p-value
X_1	1.32E+00	5.24E-01	2.51	1.20E-02
X_2	7.80E-01	1.39E-01	5.63	1.84E-08
X_3	9.79E-02	4.32E-02	2.27	2.35E-02
X_4	-1.94E-01	3.01E-02	-6.44	1.21E-10
$X_1(Q)$	-8.52E-03	3.17E-03	-2.68	7.30E-03
$X_4(Q)$	3.11E-04	4.03E-05	7.71	1.26E-14
X_1 by X_4	-1.63E-03	6.01E-04	-2.71	6.70E-03
X_2 by X_4	-1.22E-03	1.96E-04	-6.21	5.44E-10

Source: Author (2023).

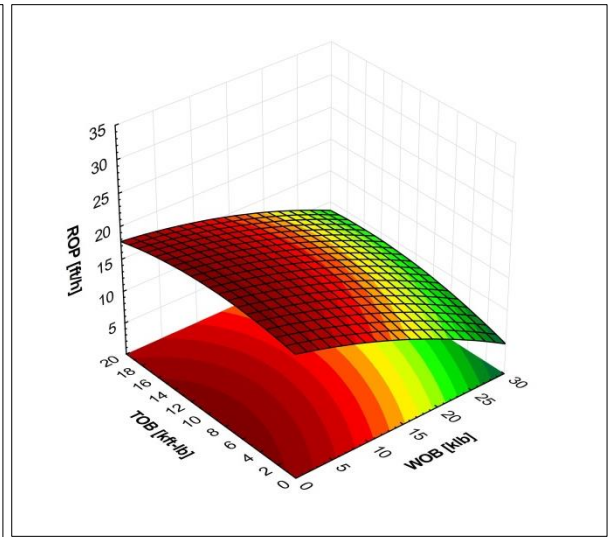
The analysis of Table 4 reveals the effects of factors on ROP, including the effect of two second-order interactions, namely: WOB vs. WOB and FLOW vs. FLOW; and the effect of two first-order interactions: WOB vs. FLOW and RPM vs. FLOW. For the factors shown in Table 4, the statistical model for predicting ROP is expressed by equation (22). In addition, the surface plots for the interactions between input variables and ROP are shown in Figure 27.

$$\begin{aligned} \text{ROP} = & 1.32 X_1 + 7.80\text{E-}01 X_2 + 9.79\text{E-}02 X_3 - 1.94\text{E-}01 X_4 - 8.52\text{E-}03 X_1^2 + \\ & 3.11\text{E-}04 X_4^2 - 1.63\text{E-}03 X_1 * X_4 - 1.22\text{E-}03 X_2 * X_4 \end{aligned} \quad (22)$$

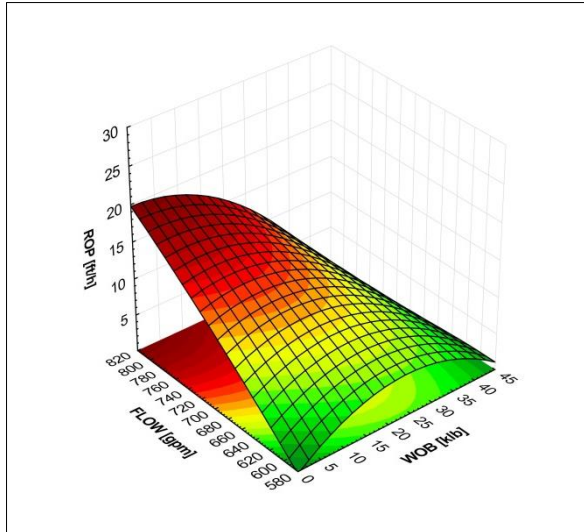
Figure 27 - surface plots: ROP vs. WOB and RPM; b) ROP vs. WOB and TOB; c) ROP vs. WOB and FLOW; d) ROP vs. RPM and TOB; e) ROP vs. RPM and FLOW; f) ROP vs. TOB and FLOW.



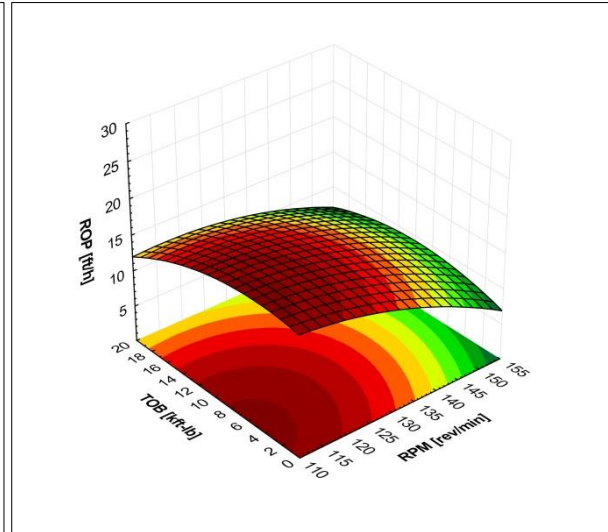
(a)



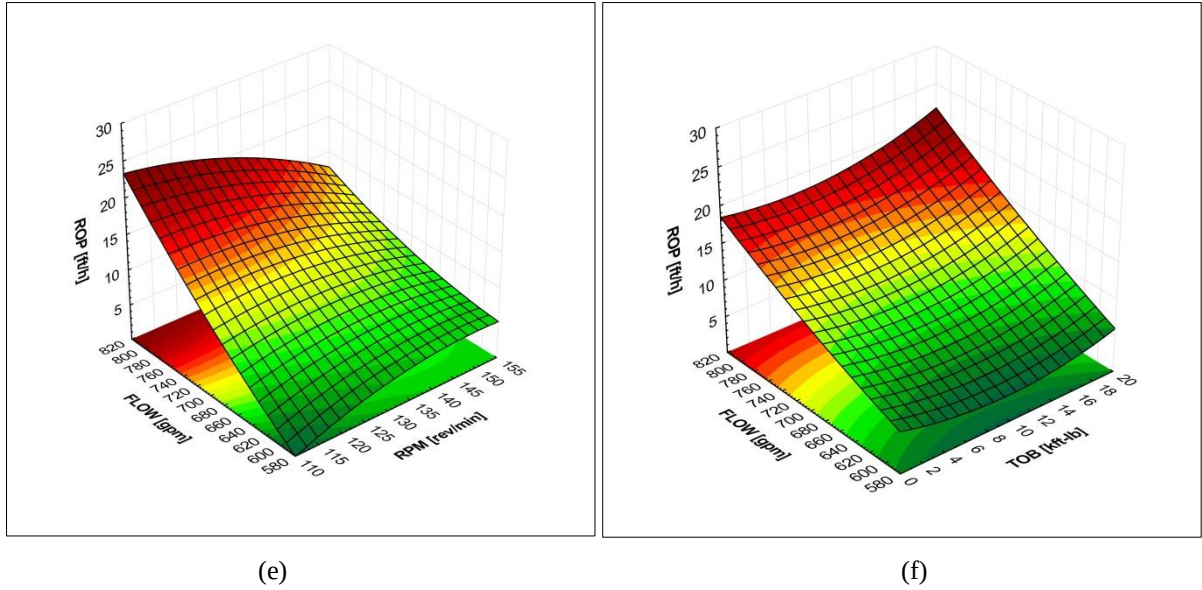
(b)



(c)



(d)



Source: Author (2023).

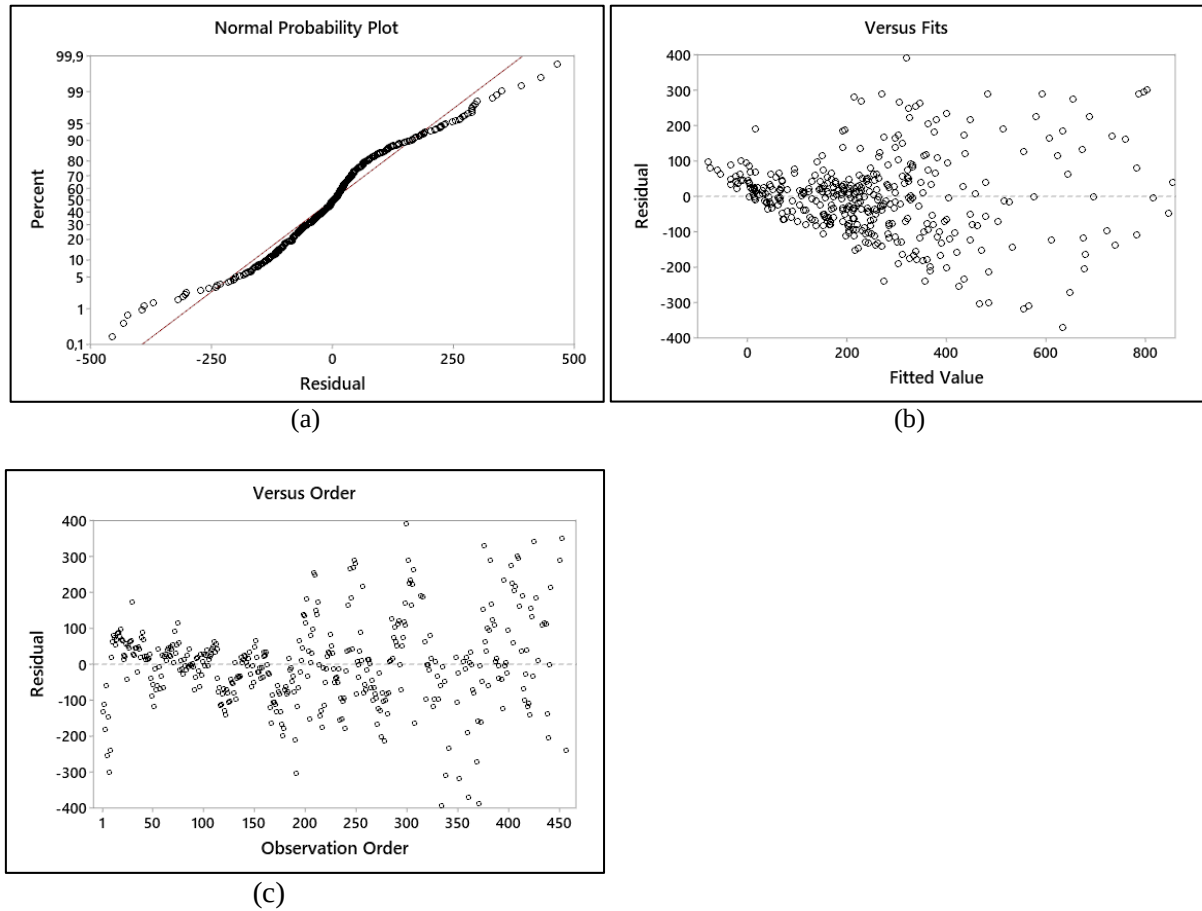
Figure 27-a shows that the increase in WOB value from 1.09 up to 43.31 [klb] causes a decrease in ROP value. Similar behavior is seen in Figure 27-b, however, the WOB effect is lower when compared with the previous Figure. The reduction of ROP by increasing WOB probably occurs due to an operation beyond the foundering point.

For all interactions, the RPM value should be maintained at approximately 110-120 [rev/min]. The increase in RPM value to 151.77 [rev/min] causes reduced drill-bit stability and consequently, a decrease in ROP. High ROP values can be obtained using the high flow-rate. The increase in flow-rate from 594.86 up to 803.32 [gpm] causes the transport of gravel at higher rates and consequently, a more efficient downhole and annular cleaning. The inefficient hole cleaning can lead the drill-bit to get stuck, causing stick-slip and whirl, as seen in Figure 17 (HEGDE et al., 2019).

4.2.2.2 Analysis of MSE

As seen in the previous section, residual plots and coefficients of determination (R^2) were initially used to evaluate the model's prediction capability. Figure 28 presents the residual plots of regression, after an analysis of atypical observations, where large residuals and atypical values were removed.

Figure 28 - Residual plots: a) normal probability plot; b) versus fit; c) versus order.



Source: Author (2023).

The model presents a good fit that can be verified through the R^2 and R_{adj}^2 of 91.92 and 91.08%, respectively. Visual analysis of residual plots indicates a violation of the regression model supposition for the fitted data. The Breusch-Pagan test revealed a violation of the homoscedasticity assumption, i.e., the null hypothesis of homoscedasticity of the residuals can be rejected.

Thus, the model was re-estimated using the method to obtain heteroscedasticity-consistent standard errors (variant HC2). Table 5 shows the estimates of the significant effects of these factors on the MSE using a 5% level of significance. For comparison purposes, the model was re-estimated using the HC0, HC1, and HC3 variants as can be seen in Tables 16, 17, and 18, respectively (Appendix B).

Table 5 - Effect of factors on MSE.

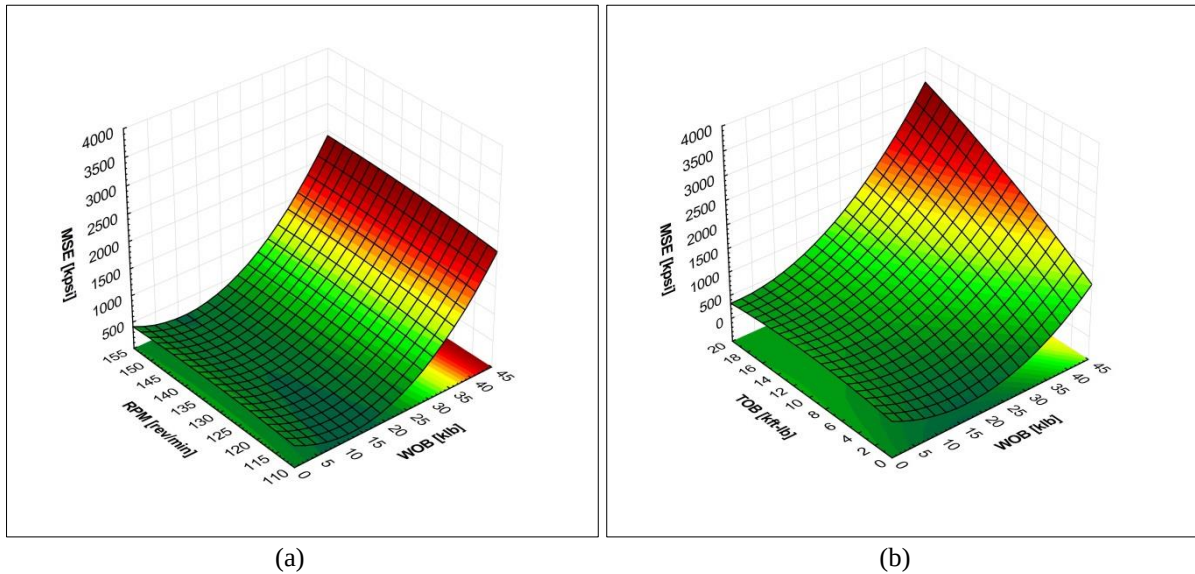
Factor	Effect	Standard deviation	T-value	p-value
X ₁	-1.46E+02	3.33E+01	-4.37	1.22E-05
X ₂	-3.35E+01	1.35E+01	-2.48	1.31E-02
X ₃	3.03E+02	2.62E+01	11.55	7.01E-31
X ₄	9.81E+00	3.34E+00	2.93	3.40E-03
X ₁ (Q)	1.08E+00	2.14E-01	5.05	4.38E-07
X ₄ (Q)	-1.22E-02	3.90E-03	-3.14	1.70E-03
X ₁ by X ₂	2.63E-01	1.29E-01	2.05	4.09E-02
X ₁ by X ₄	1.09E-01	2.86E-02	3.81	1.00E-04
X ₂ by X ₄	4.28E-02	1.55E-02	2.77	5.70E-03
X ₃ by X ₄	-3.46E-01	3.30E-02	-10.48	1.12E-25

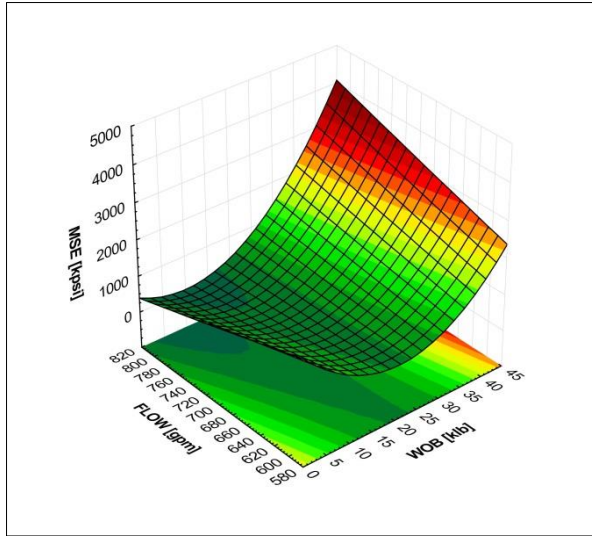
Source: Author (2023).

The analysis of Table 5 reveals the effects of factors on MSE, including the effect of two second-order interactions, namely: WOB vs. WOB, and FLOW vs. FLOW; and the effect of four first-order interactions: WOB vs. RPM, WOB vs. FLOW, RPM vs. FLOW and TOB vs. FLOW. For the factors shown in Table 5, the statistical model for predicting MSE is expressed by equation (23). And, the surface plots for the interactions between input variables and MSE are shown in Figure 29

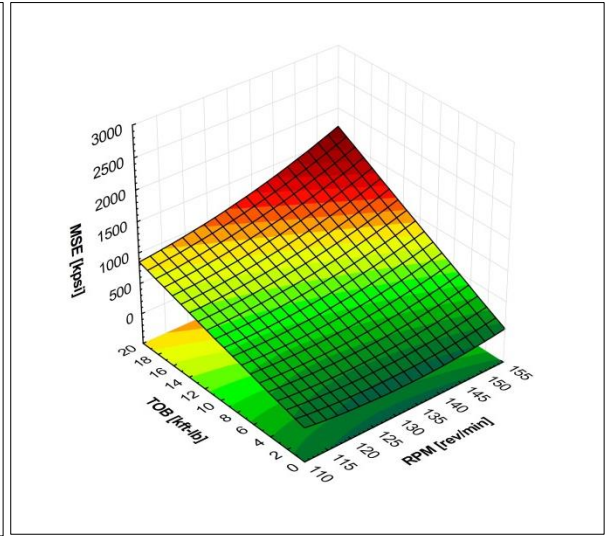
$$\text{MSE} = -1.46\text{E}+02 X_1 - 3.35\text{E}+01 X_2 + 3.03\text{E}+02 X_3 + 9.81 X_4 + 1.08 X_1^2 - 1.22\text{E}-02 X_4^2 + 2.63\text{E}-01 X_1 * X_2 + 1.09\text{E}-01 X_1 * X_4 + 4.28\text{E}-02 X_2 * X_4 - 3.46\text{E}-01 X_3 * X_4 \quad (23)$$

Figure 29 - Surface plots: MSE vs. WOB and RPM; b) MSE vs. WOB and TOB; c) MSE vs. WOB and FLOW; d) MSE vs. RPM and TOB; e) MSE vs. RPM and FLOW; f) MSE vs. TOB and FLOW.

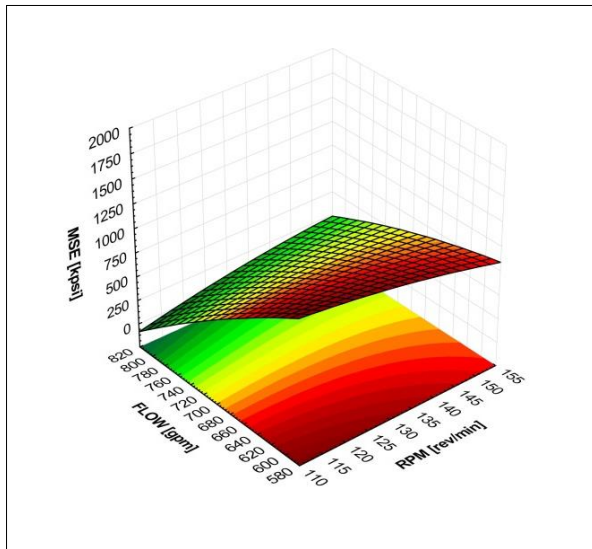




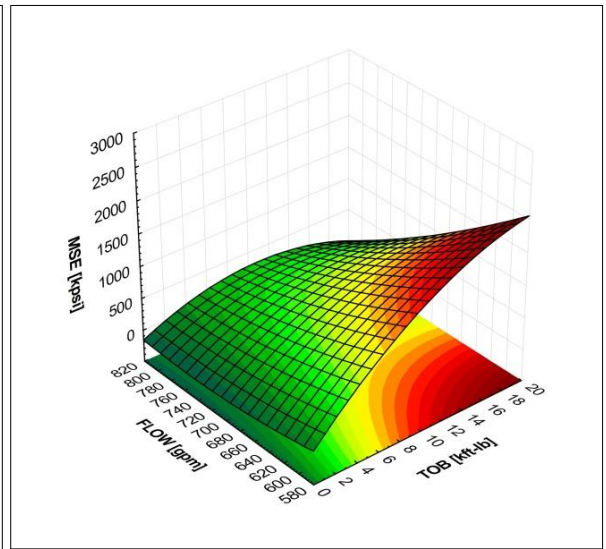
(c)



(d)



(e)



(f)

Source: Author (2023).

Differently from the behavior previously seen in Figure 27, WOB should be adjusted to values from 10 up to 25 [klb]. This fact occurs due to two distinct behaviors presented in the WOB plots. Initially, increasing the WOB value up to 10-25 [klb] leads to a decrease in MSE value, however, the use of WOB values above 25 [klb] causes a large increase in MSE values and causes undesirable effects, such as vibrations.

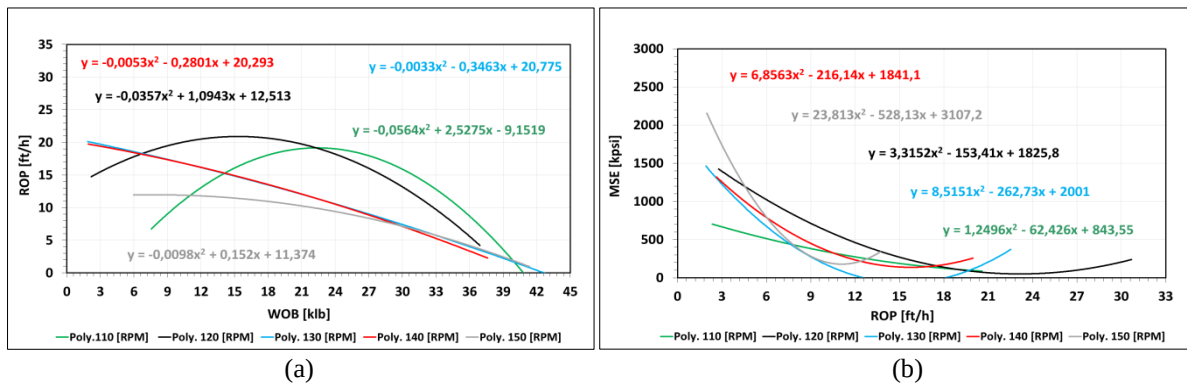
The RPM and TOB values should be adjusted for low values, while the flow-rate should be maintained at high values. RPM and flow-rate follow a similar behavior to that presented in Figure 27 and can be explained by the drill-bit stability and efficient hole cleaning, respectively.

4.3 DRILL-RATE TEST

The Drill-Rate Test (DRT) goal, detailed in section 2.5, is to obtain WOB and RPM values that result in safe and efficient drilling. DRT is a pre-operational test that should be carried out always that occurs changes in the drilling of actual formation, i.e., lithology and static drilling parameters. For this reason, DRT must be carried out in an agile and fast way.

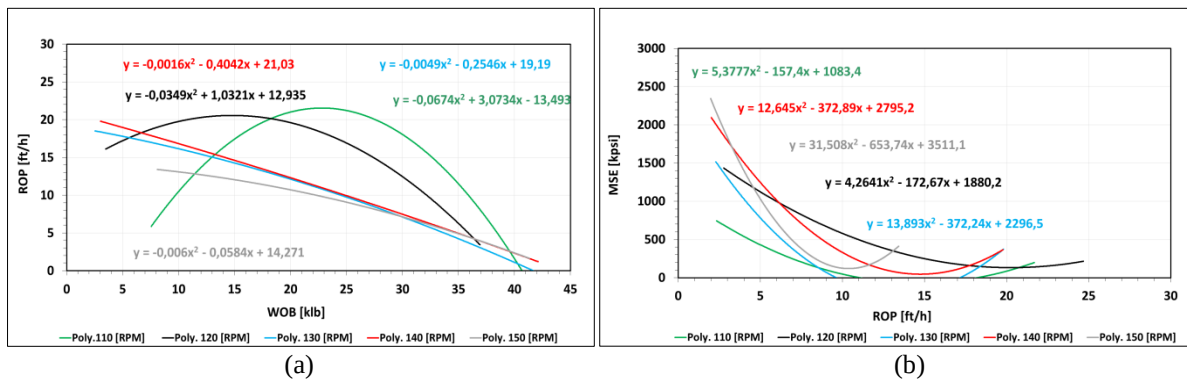
The dataset was initially separated by different RPM values (110, 120, 130, 140, and 150 [rev/min]) and posteriorly, the mean of the WOB, ROP, and MSE values was performed for WOB's groups of 3, 5, and 7 [klb]. Figures 30, 31 and 32 show the relation between the ROP vs. WOB plot and the MSE vs. ROP plot for WOB's groups of 3, 5, and 7 [klb], respectively.

Figure 30 - WOB's groups of 3 [klb]: (a) ROP vs. WOB plot; (b) MSE vs. ROP plot.



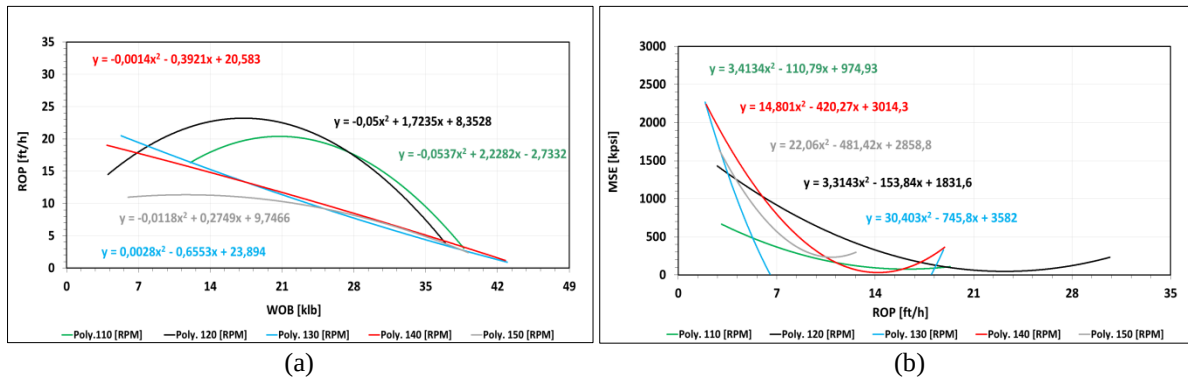
Source: Author (2023).

Figure 31 - WOB's groups of 5 [klb]: (a) ROP vs. WOB plot; (b) MSE vs. ROP plot.



Source: Author (2023).

Figure 32 - WOB's groups of 7 [klb]: (a) ROP vs. WOB plot; (b) MSE vs. ROP plot.



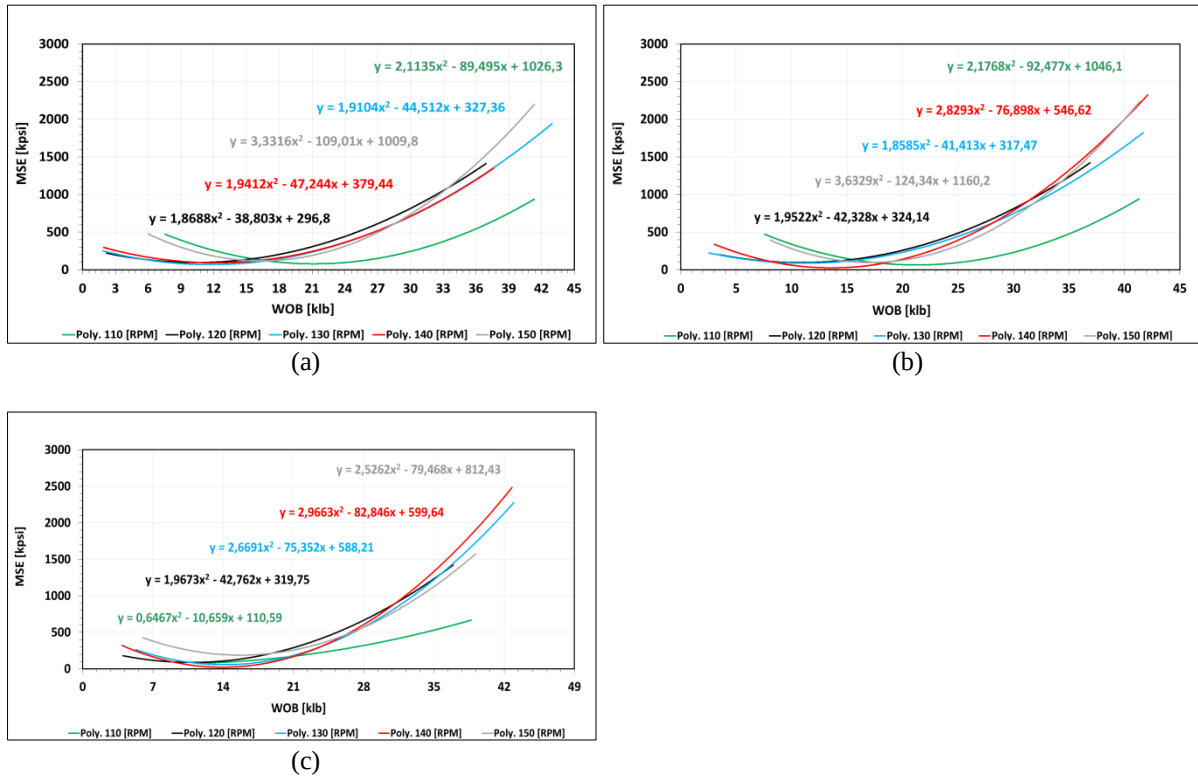
Source: Author (2023).

Analyzing Figures 30-a, 31-a and 32-a can be observed that only the curves of 110 and 120 [rev/min] present regions II, III and IV. The other curves uncited only show region IV, indicating an inefficient drilling process, where the increased WOB value causes a decrease in ROP value.

Analyzing Figures Figure 30-b, 31-b and 32-b can be observed similar behavior for all curves, where lower ROP cause higher MSE values. Among all analyzed curves, the that presents the lowest MSE value is 130 [rev/min]. The minimum value of MSE for this curve is 6.72 [kpsi]. However, as seen this curve only presents the third region, i.e., the inefficient drilling process. The 110 and 120 [rev/min] curves present the minimum values of 59.52 and 118.87 [kpsi], respectively. Thus, these rotary speed values will allow obtaining the highest ROP values, in addition to avoiding the problems seen in region IV of Figure 18.

A new concept of pre-operational tests based on MSE drill-rate tests was presented by Nascimento (2019). It has been a new focus in the O&G industry to relate the drilling performance to the MSE dispended in the drilling activities, and not the achievement of the highest ROP, as it has usually been applied. In this sense, it is possible to change the focus when analyzing drill-rate tests, replacing the interpreting relation WOB vs. ROP by WOB vs. MSE. Figure 33 shows the relation between the MSE vs. WOB plot for several grouping of WOB (3, 5, and 7 [klb]).

Figure 33 - Relation between the MSE vs. WOB plot for several grouping: (a) 3 [klb]; (b) 5 [klb]; (c) 7 [klb].



Source: Author (2023).

Figure 33 shows MSE drill-rate test curve to reflect operational efficiency. All curves show similar behavior for low WOB values. However, from WOB values that exceed 30 [klb], the 110 [rev/min] curve is the only one that presents an MSE value below 1000 [kpsi]. These facts shown in Figures 30, 31, 32 and 33 prove that there is an ideal combination between WOB and RPM that allows obtaining a high ROP and a low MSE value.

4.4 MULTI-OBJECTIVE OPTIMIZATION

Before starting the optimization process, choosing the best combination of RPM and WOB is necessary. The curves for RPM of 110 and 120 [rev/min] present considerable similarity to Figure 18. For this reason, these are the RPMs chosen for further development of the multi-objective optimization in this study.

The following tables (Tables 6 to 12) show the results obtained from multi-objective optimization for the rotary speed of 110 and 120 [rev/min] and WOB's groups of 3, 5, and 7 [klb]. Table 6 shows the results of the multi-objective optimization for the grouping of 3 [klb].

Table 6 - Multi-objective optimization for grouping of 3 [klb].

	110 [rev/min]				120 [rev/min]			
	WOB [klb]	ROP [ft/h]	MSE [kpsi]	Desirability -	WOB [klb]	ROP [ft/h]	MSE [kpsi]	Desirability -
01	22.39	19.14	81.99	0.92	16.61	21.14	158.30	0.65
02	22.30	19.14	81.56	0.92	16.24	21.14	151.17	0.68
03	22.21	19.14	81.14	0.93	15.86	21.12	144.24	0.71
04	22.11	19.14	80.73	0.93	15.46	21.09	137.57	0.74
05	22.01	19.13	80.33	0.94	15.04	21.04	131.20	0.77
06	21.89	19.13	79.96	0.94	14.58	20.97	125.24	0.81
07	21.77	19.12	79.62	0.95	14.09	20.88	119.77	0.84
08	21.64	19.11	79.32	0.96	13.56	20.76	114.96	0.88
09	21.50	19.10	79.07	0.96	12.98	20.60	111.01	0.92
10	21.34	19.08	78.91	0.97	12.34	20.38	108.24	0.97
11	21.17	19.06	78.84	0.97	11.61	20.10	107.15	1.02

Source: Author (2023).

Comparing the values shown in scenario 1 of Table 6, it is noted that the maximum values reached by ROP and MSE are 19.14 [ft/h] and 81.99 [kpsi] for RPM of 110 [rev/min], and 21.14 [ft/h] and 158.30 [kpsi] for RPM of 120 [rev/min]. Note that, an increase in ROP in 2.00 [ft/h] leads to an increase in MSE in 76.31 [kpsi] and a decrease in WOB of 5.78 [klb]. This improvement of 2.00 [ft/hr] in ROP is considerably small for the large increase in MSE drawn. Scenario 11 for RPM of 120 [rev/min] shows good results. For this, a ROP of 20.10 [ft/h] is obtained when applying a WOB of 11.61 [klb]. Comparing these values with scenario 1 for RPM of 110 [rev/min], it is possible to obtain better ROP using half the WOB value, however, this leads to an MSE increase of 26.16 [kpsi].

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

Table 7 - Multi-objective optimization for grouping of 5 [klb].

	110 [rev/min]				120 [rev/min]			
	WOB [klb]	ROP [ft/h]	MSE [kpsi]	Desirability -	WOB [klb]	ROP [ft/h]	MSE [kpsi]	Desirability -
01	22.79	21.53	69.22	0.99	14.77	20.55	124.86	0.81
02	22.68	21.53	68.52	0.99	14.46	20.55	120.37	0.82
03	22.57	21.53	67.82	0.99	14.14	20.54	116.06	0.84
04	22.45	21.53	67.14	0.99	13.81	20.52	111.97	0.86
05	22.32	21.52	66.48	0.99	13.46	20.49	108.14	0.88
06	22.17	21.51	65.86	0.99	13.09	20.46	104.62	0.90
07	22.02	21.49	65.28	0.99	12.70	20.40	101.48	0.92
08	21.85	21.47	64.77	0.99	12.28	20.34	98.79	0.94
09	21.66	21.45	64.35	0.99	11.84	20.25	96.66	0.96
10	21.46	21.41	64.06	0.99	11.36	20.15	95.23	0.99
11	21.24	21.37	63.95	0.99	10.84	20.01	94.70	1.01

Source: Author (2023).

Through Table 7 can be seen that the WOB, ROP, and MSE value range for RPM of 110 [rev/min] varies 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 RPM of 110 [rev/min] and for RPM of 120 [rev/min] are compared. Good ROP values are obtained through lower WOB, however, this combination of parameters leads to high MSE values at the same time, which is not desired. Table 8 shows the results of the multi-objective optimization for the grouping of 7 [klb].

Table 8 - Multi-objective optimization for 110 rev/min and 7 [klb].

	110 [rev/min]				120 [rev/min]			
	WOB [klb]	ROP [ft/h]	MSE [kpsi]	Desirability -	WOB [klb]	ROP [ft/h]	MSE [kpsi]	Desirability -
01	20.75	20.38	167.90	1.06	17.23	23.20	167.19	0.73
02	20.20	20.37	159.26	1.04	16.82	23.19	157.10	0.75
03	19.61	20.31	150.26	1.02	16.37	23.17	147.11	0.77
04	18.95	20.21	140.85	1.00	15.90	23.11	137.29	0.80
05	18.21	20.04	131.02	0.98	15.39	23.03	127.70	0.82
06	17.38	19.77	120.73	0.97	14.84	22.92	118.45	0.85
07	16.42	19.38	109.97	0.96	14.23	22.75	109.70	0.88
08	15.28	18.78	98.73	0.96	13.56	22.53	101.68	0.92
09	13.86	17.83	87.08	0.96	12.80	22.22	94.77	0.95
10	12.04	16.31	76.00	0.98	11.92	21.79	89.58	0.99
11	12.04	16.31	76.00	1.00	10.86	21.17	87.37	1.04

Source: Author (2023).

Table 8 shows similar MSE values for all the scenarios under analysis. However, for 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 WOB lower than 11 [klb].

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

4.5 ANALYSIS OF COSTS

Ultra-deep drilling operations in the Pre-salt fields can reach costs of around 1.3 million [USD] per day (NASCIMENTO et al., 2017; PINHEIRO et al., 2019). Considering the daily operating cost presented, Table 9 shows the cost and time to drill zone II (inefficient zone) exhibited in Figure 25.

Table 9 - Cost analysis of parameters used during the drilling of zone 2.

WOB [klb]	ROP [ft/h]	RPM [rev/min]	Depth Range [ft]	Time [h]	Drilling Cost [USD]
2.30 – 42.90	1.29 – 13.97	110 - 150	97.01	25.42	1,387,335.52

Source: Author (2023).

The inefficient zone has an extension of 87 ft (26.5 m). For this depth range, it was registered a total operational time of 25.42 hours, which may reflect a total cost of approximately USD 1,387,335.52. This fact shows that the ROP for this zone was very low, with mean values of approximately 3.42 [ft/h] or 1.04 [m/h].

The following tables show the costs and time that would take to drill zone II (inefficient zone) after carrying out the drill-rate test (pre-operational test) and multi-objective optimization, using the parameters obtained and presented in Tables 6, 7 and 8, respectively.

Table 10 - Cost analysis related to the parameters and values presented in Table 6.

	110 [rev/min]				120 [rev/min]			
	Time	Cost	Time	Cost	Time	Cost	Time	Cost-saving
	[h]	[USD]	Saving [h]	Saving [USD]	[h]	[USD]	Saving [h]	[USD]
01	5.07	274,454.74	20.38	1,103,880.78	4.59	248,473.47	20.86	1,129,862.05
02	5.07	274,460.73	20.38	1,103,874.79	4.59	248,537.55	20.86	1,129,797.97
03	5.07	274,480.33	20.38	1,103,855.20	4.59	248,743.58	20.85	1,129,591.94
04	5.07	274,516.37	20.38	1,103,819.15	4.60	249,116.44	20.85	1,129,219.08
05	5.07	274,572.34	20.38	1,103,763.18	4.61	249,688.23	20.84	1,128,647.29
06	5.07	274,652.57	20.38	1,103,682.96	4.62	250,501.27	20.82	1,127,834.26
07	5.07	274,762.40	20.37	1,103,573.12	4.65	251,612.70	20.80	1,126,722.82
08	5.08	274,908.61	20.37	1,103,426.91	4.67	253,102.20	20.77	1,125,233.32
09	5.08	275,099.78	20.37	1,103,235.74	4.71	255,085.20	20.74	1,123,250.32
10	5.08	275,347.00	20.36	1,102,988.52	4.76	257,737.57	20.69	1,120,597.95
11	5.09	275,664.76	20.36	1,102,670.76	4.82	261,346.11	20.62	1,116,989.41

Source: Author (2023).

Table 11 - Cost analysis related to the parameters and values presented in Table 7.

	110 [rev/min]				120 [rev/min]			
	Time	Cost	Time	Cost	Time	Cost	Time	Cost-saving
	[h]	[USD]	Saving [h]	Saving [USD]	[h]	[USD]	Saving [h]	[USD]
01	4.50	243,975.73	20.94	1,134,359.79	4.72	255,613.02	20.73	1,122,722.50
02	4.50	243,984.48	20.94	1,134,351.04	4.72	255,653.37	20.73	1,122,682.15
03	4.50	244,013.22	20.94	1,134,322.30	4.72	255,781.77	20.72	1,122,553.75
04	4.51	244,066.37	20.94	1,134,269.15	4.73	256,011.05	20.72	1,122,324.47
05	4.51	244,149.41	20.94	1,134,186.11	4.73	256,356.99	20.71	1,121,978.53
06	4.51	244,269.24	20.94	1,134,066.28	4.74	256,839.30	20.70	1,121,496.22
07	4.51	244,434.60	20.93	1,133,900.92	4.75	257,482.95	20.69	1,120,852.57
08	4.52	244,656.74	20.93	1,133,678.78	4.77	258,320.23	20.68	1,120,015.29
09	4.52	244,950.32	20.92	1,133,385.21	4.79	259,393.84	20.66	1,118,941.68
10	4.53	245,334.80	20.92	1,133,000.72	4.81	260,761.82	20.63	1,117,573.70
11	4.54	245,836.60	20.91	1,132,498.93	4.85	262,505.79	20.60	1,115,829.73

Source: Author (2023).

Table 12 - Cost analysis related to the parameters and values presented in Table 8.

	110 [rev/min]				120 [rev/min]			
	Time [h]	Cost [USD]	Time Saving [h]	Cost Saving [USD]	Time [h]	Cost [USD]	Time Saving [h]	Cost-saving [USD]
01	4.76	257,756.71	20.69	1,120,578.81	4.18	226,437.22	21.27	1,151,898.30
02	4.76	257,958.87	20.68	1,120,376.65	4.18	226,521.81	21.26	1,151,813.72
03	4.77	258,645.50	20.67	1,119,690.02	4.19	226,797.86	21.26	1,151,537.66
04	4.80	259,977.19	20.65	1,118,358.34	4.20	227,306.88	21.25	1,151,028.64
05	4.84	262,196.68	20.61	1,116,138.84	4.21	228,104.99	21.24	1,150,230.53
06	4.91	265,692.15	20.54	1,112,643.37	4.23	229,270.34	21.21	1,149,065.18
07	5.01	271,132.81	20.44	1,107,202.72	4.26	230,915.94	21.18	1,147,419.58
08	5.17	279,802.66	20.28	1,098,532.87	4.31	233,213.11	21.14	1,145,122.42
09	5.44	294,609.98	20.01	1,083,725.54	4.37	236,438.47	21.08	1,141,897.05
10	5.95	322,154.80	19.50	1,056,180.72	4.45	241,080.09	21.00	1,137,255.44
11	5.95	322,154.80	19.50	1,056,180.72	4.58	248,122.51	20.87	1,130,213.01

Source: Author (2023).

Tables 10, 11, and 12 show the time, cost, time-saving, and cost-saving to drilling the inefficient zone through WOB's grouping of 3, 5, and 7 [klb] and 110 and 120 [rev/min]. The cost and time to drill this inefficient zone through the parameters obtained from pre-operational tests ranged from 226,437.22 to 322,154.80 [USD] and 4.18 to 5.95 [h], respectively. In addition, comparing values shown in Tables 10, 11, and 12 with values in Table 9, the cost-saving and time-saving values range from USD 1,056,180.72 to 1,151,898.30 and 19.50 to 21.27 [h], respectively.

5 CONCLUSION

In this dissertation, response surface methodology and multi-objective optimization based on pre-operational drilling tests, linked to a new recent methodology aiming at improving the drilling process through a possible ideal combination of ROP and MSE were performed. DRT methodology was mainly based on 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 dissertation are:

- The representation of drilling parameters through 2D plots as a function of depth allowed identifying the inefficient drilling zone and the possible parameters responsible for this inefficiency;
- From the statistical analysis, it was possible to identify the input parameters that had a significant effect on the response variables. In addition, statistical models can predict all trends presented by the dataset, considering a 95% confidence level;
- The new concept of pre-operational tests based on MSE showed to promise effective improvements in the drilling processes;
- The combination of the highest ROP and the lowest MSE allows to perform an efficient drilling operation, transpering machinery, and equipment overload, and subsequently possible ways to improve operational efficiency;
- Desirability Method, as per Derringer and Suich (1980), allowed optimizing the drilling process satisfactorily, which may be extended to other operations and scenarios;
- For all WOB intervals of 3, 5, and 7 [klb] good fit of parameters was obtained, and as an interesting outcome for the industry, DRT with 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 1,056,180.72 to 1,151,898.30 and 19.50 to 21.27 [h], respectively.

For future work:

- Expand this analysis to more field datasets from real Pre-salt and geothermal energy operations;
- Apply the methodology of this dissertation in a didactic drilling rig bench to test the efficiency of the proposal on a laboratory scale in real-time;
- To develop a software through the methodology presented in this dissertation to be used directly in the industry.

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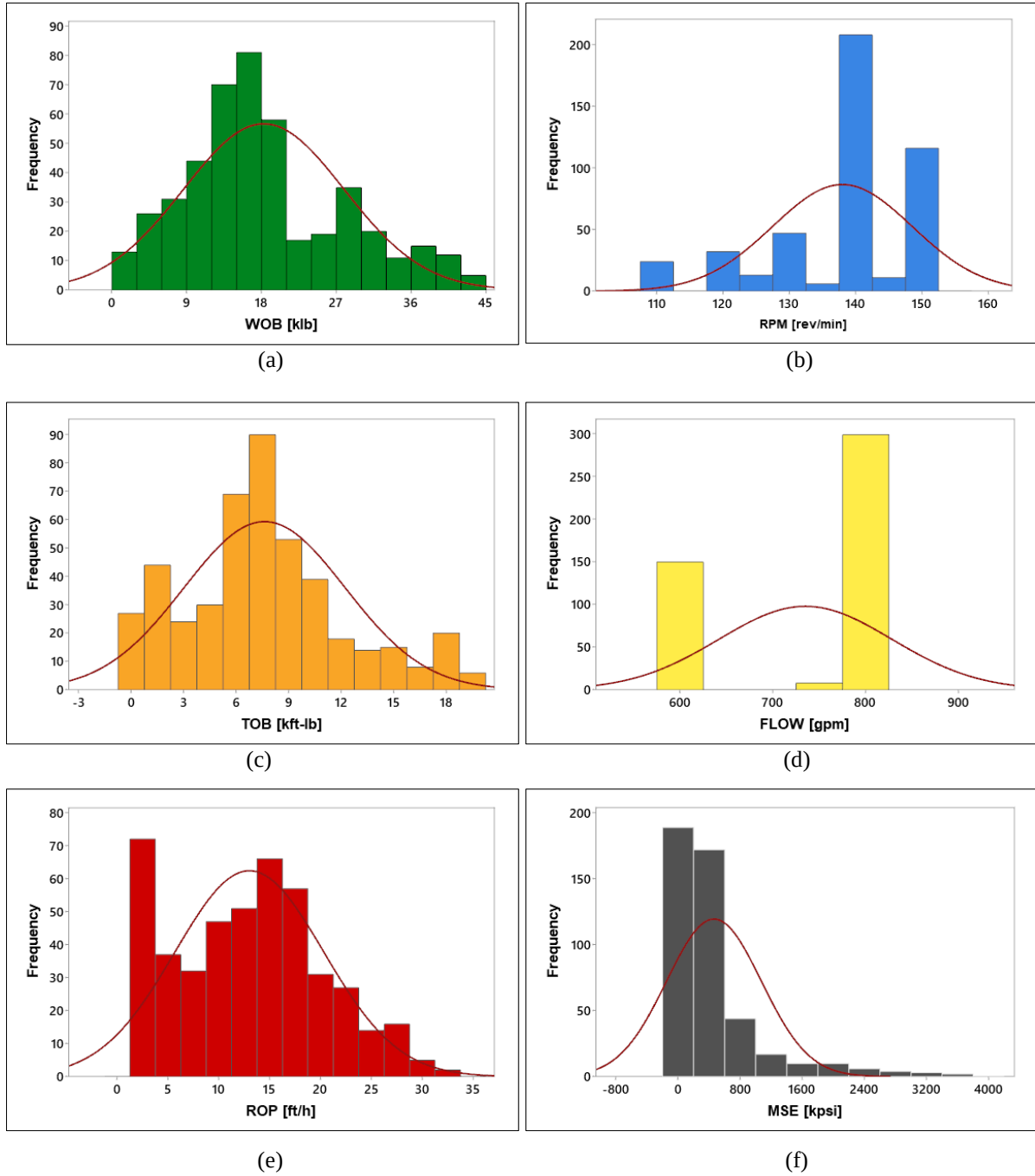
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APPENDIX A

Figure 34 - Distribution of dataset.



Source: Author (2023).

APPENDIX B

Table 13 - Effect of factors on ROP using heteroscedasticity-consistent standard errors
(variant HC0).

Factor	Effect	Standard deviation	T-value	p-value*
X ₁	1.32E+00	4.96E-01	2.65	8.00E-03
X ₂	7.80E-01	1.36E-01	5.71	1.11E-08
X ₃	9.79E-02	4.27E-02	2.29	2.19E-02
X ₄	-1.94E-01	2.95E-02	-6.56	5.26E-11
X ₁ (Q)	-8.52E-03	3.01E-03	-2.83	4.70E-03
X ₄ (Q)	3.11E-04	3.96E-05	7.85	4.34E-15
X ₁ by X ₄	-1.63E-03	5.73E-04	-2.84	4.50E-03
X ₂ by X ₄	-1.22E-03	1.93E-04	-6.29	3.09E-10

*statistical significance of the p-value is 0.05.

Source: Author (2023).

Table 14- Effect of factors on ROP using heteroscedasticity-consistent standard errors
(variant HC1).

Factor	Effect	Standard deviation	T-value	p-value*
X ₁	1.32E+00	5.01E-01	2.63	8.50E-03
X ₂	7.80E-01	1.38E-01	5.66	1.48E-08
X ₃	9.79E-02	4.31E-02	2.27	2.31E-02
X ₄	-1.94E-01	2.98E-02	-6.51	7.74E-11
X ₁ (Q)	-8.52E-03	3.04E-03	-2.80	5.10E-03
X ₄ (Q)	3.11E-04	4.00E-05	7.78	7.51E-15
X ₁ by X ₄	-1.63E-03	5.78E-04	-2.82	4.80E-03
X ₂ by X ₄	-1.22E-03	1.95E-04	-6.24	4.40E-10

*statistical significance of the p-value is 0.05.

Source: Author (2023).

Table 15 - Effect of factors on ROP using heteroscedasticity-consistent standard errors (variant HC3).

Factor	Effect	Standard deviation	T-value	p-value*
X ₁	1.32E+00	5.56E-01	2.37	1.79E-02
X ₂	7.80E-01	1.41E-01	5.54	3.07E-08
X ₃	9.79E-02	4.37E-02	2.24	2.50E-02
X ₄	-1.94E-01	3.07E-02	-6.31	2.82E-10
X ₁ (Q)	-8.52E-03	3.36E-03	-2.54	1.12E-02
X ₄ (Q)	3.11E-04	4.11E-05	7.57	3.71E-14
X ₁ by X ₄	-1.63E-03	6.34E-04	-2.57	1.02E-02
X ₂ by X ₄	-1.22E-03	1.99E-04	-6.12	9.60E-10

*statistical significance of the p-value is 0.05.

Source: Author (2023).

Table 16 - Effect of factors on MSE using heteroscedasticity-consistent standard errors (variant HC0).

Factor	Effect	Standard deviation	T-value	p-value*
X ₁	-1.46E+02	3.12E+01	-4.67	3.09E-06
X ₂	-3.35E+01	1.26E+01	-2.66	7.90E-03
X ₃	3.03E+02	2.49E+01	12.17	4.45E-34
X ₄	9.81E+00	3.10E+00	3.17	1.50E-03
X ₁ (Q)	1.08E+00	2.03E-01	5.31	1.07E-07
X ₄ (Q)	-1.22E-02	3.62E-03	-3.39	7.00E-04
X ₁ by X ₂	2.63E-01	1.20E-01	2.19	2.85E-02
X ₁ by X ₄	1.09E-01	2.73E-02	3.99	6.66E-05
X ₂ by X ₄	4.28E-02	1.45E-02	2.96	3.10E-03
X ₃ by X ₄	-3.46E-01	3.14E-02	-11.03	2.87E-28

*statistical significance of the p-value is 0.05.

Source: Author (2023).

Table 17- Effect of factors on MSE using heteroscedasticity-consistent standard errors (variant HC1).

Factor	Effect	Standard deviation	T-value	p-value*
X ₁	-1.46E+02	3.16E+01	-4.61	4.08E-06
X ₂	-3.35E+01	1.28E+01	-2.62	8.70E-03
X ₃	3.03E+02	2.52E+01	12.02	2.78E-33
X ₄	9.81E+00	3.14E+00	3.13	1.80E-03
X ₁ (Q)	1.08E+00	2.06E-01	5.25	1.53E-07
X ₄ (Q)	-1.22E-02	3.66E-03	-3.34	8.00E-04
X ₁ by X ₂	2.63E-01	1.22E-01	2.16	3.05E-02
X ₁ by X ₄	1.09E-01	2.76E-02	3.94	8.18E-05
X ₂ by X ₄	4.28E-02	1.47E-02	2.92	3.50E-03
X ₃ by X ₄	-3.46E-01	3.17E-02	-10.89	1.29E-27

*statistical significance of the p-value is 0.05.

Source: Author (2023).

Table 18 - Effect of factors on MSE using heteroscedasticity-consistent standard errors (variant HC3).

Factor	Effect	Standard deviation	T-value	p-value*
X ₁	-1.46E+02	3.58E+01	-4.07	4.74E-05
X ₂	-3.35E+01	1.46E+01	-2.30	2.13E-02
X ₃	3.03E+02	2.76E+01	10.96	5.81E-28
X ₄	9.81E+00	3.64E+00	2.70	7.00E-03
X ₁ (Q)	1.08E+00	2.26E-01	4.79	1.67E-06
X ₄ (Q)	-1.22E-02	4.23E-03	-2.89	3.80E-03
X ₁ by X ₂	2.63E-01	1.39E-01	1.90	5.80E-02
X ₁ by X ₄	1.09E-01	3.00E-02	3.63	3.00E-04
X ₂ by X ₄	4.28E-02	1.66E-02	2.58	1.00E-02
X ₃ by X ₄	-3.46E-01	3.48E-02	-9.95	2.65E-23

*statistical significance of the p-value is 0.05.

Source: Author (2023).

APPENDIX C

Table 19- Pre-salt dataset.

DEPTH [ft/h]	RPM [rev/min]	TOB [kft-lb]	WOB [klb]	FLOW [gpm]	ROP [ft/h]	DEPTH [ft/h]	RPM [rev/min]	TOB [kft-lb]	WOB [klb]	FLOW [gpm]	ROP [ft/h]
17054.00	101.15	4.66	15.10	752.28	8.98	17066.50	100.83	5.60	13.06	752.28	13.42
17054.50	100.70	8.15	21.89	752.28	8.58	17067.00	100.98	7.38	17.21	752.28	14.51
17055.00	100.81	9.09	18.06	752.28	8.40	17067.50	100.98	6.13	15.48	752.28	14.92
17055.50	100.90	4.27	12.40	752.28	8.37	17068.00	101.00	5.91	15.36	752.28	14.95
17056.00	100.49	9.30	17.92	752.28	10.43	17068.50	100.04	12.90	17.70	752.76	15.50
17056.50	101.20	3.87	15.06	752.28	12.29	17069.00	108.78	11.67	17.84	752.28	15.82
17057.00	100.83	6.13	11.18	752.28	11.35	17069.50	110.48	5.20	15.50	752.28	16.52
17057.50	100.73	8.02	19.48	752.28	11.55	17070.00	108.39	10.77	14.78	752.28	16.08
17058.00	100.71	8.55	20.94	752.28	11.52	17070.50	110.50	3.99	13.54	752.28	16.49
17058.50	100.08	12.46	21.93	752.28	12.15	17071.00	108.74	13.74	18.26	752.28	16.95
17059.00	101.20	5.00	17.46	752.28	12.19	17071.50	110.29	8.08	15.36	752.28	16.72
17059.50	100.62	8.88	22.27	752.28	12.66	17072.00	108.57	12.41	15.46	752.28	16.98
17060.00	99.89	13.07	20.91	752.28	13.48	17072.50	110.38	1.42	13.11	752.28	18.45
17060.50	101.18	5.28	17.97	752.28	13.56	17073.00	110.08	9.87	19.23	752.28	20.41
17061.00	101.64	3.09	16.39	752.28	13.20	17073.50	110.97	4.62	16.10	752.28	21.40
17061.50	101.18	3.64	16.25	752.28	13.51	17074.00	110.46	11.24	20.58	752.28	21.68
17062.00	100.66	7.23	16.12	752.28	14.12	17074.50	101.09	30.68	12.10	752.28	22.08
17062.50	100.68	7.00	19.15	752.28	13.40	17075.00	107.01	16.41	15.98	752.28	24.17
17063.00	100.75	7.54	21.13	752.28	12.80	17075.50	110.21	8.17	16.74	752.28	24.54
17063.50	100.28	11.49	20.88	752.28	12.76	17076.00	108.71	11.42	17.32	752.28	24.74
17064.00	100.98	7.30	18.75	752.28	12.93	17076.50	108.71	11.14	19.10	801.89	28.05
17064.50	101.71	1.46	14.43	740.59	12.44	17077.00	110.08	7.33	14.33	801.89	30.32
17065.00	99.70	15.79	20.09	752.28	12.27	17077.50	107.65	17.39	20.83	801.89	28.27
17065.50	101.37	2.91	13.41	752.28	12.88	17078.00	110.57	3.67	12.74	801.89	26.49

17066.00	100.77	6.32	21.28	752.28	13.88	17078.50	110.47	0.33	16.16	801.89	24.19
17079.00	107.95	17.00	15.92	801.89	23.27	17097.00	118.43	14.75	19.37	801.89	15.05
17079.50	110.04	0.95	16.24	801.89	22.93	17097.50	119.14	3.63	11.72	803.08	16.38
17080.00	108.71	10.85	14.69	801.89	20.66	17098.00	119.84	7.89	16.09	801.89	18.22
17081.00	110.25	5.95	16.85	801.89	18.85	17098.50	118.75	12.79	11.63	801.89	21.02
17082.00	108.73	12.40	19.74	802.37	16.87	17099.00	119.54	7.94	12.19	802.37	20.73
17082.50	108.59	14.39	19.44	802.84	18.02	17099.50	119.29	7.58	9.74	801.89	20.98
17083.00	110.80	4.33	13.26	801.89	17.33	17100.00	118.86	13.52	14.27	801.89	20.91
17083.50	110.72	2.61	14.13	801.89	17.36	17100.50	120.21	4.24	9.01	801.89	22.23
17084.00	110.99	8.36	15.41	801.89	17.23	17101.00	118.84	10.33	18.68	802.37	22.69
17084.50	110.78	0.85	14.32	802.84	17.56	17101.50	119.26	11.62	18.42	801.89	30.40
17085.00	110.66	4.49	15.32	801.89	18.80	17102.00	119.22	8.14	16.82	801.89	32.12
17086.00	110.35	6.93	16.08	802.84	19.03	17102.50	118.32	18.42	21.23	801.89	30.69
17086.50	121.57	9.64	13.53	802.37	19.14	17103.00	119.67	6.32	11.16	801.89	31.26
17087.00	121.42	6.29	15.09	801.89	19.58	17103.50	130.50	6.32	5.50	801.89	27.88
17087.50	121.29	11.10	15.93	801.89	18.16	17104.00	129.90	6.30	5.70	801.89	25.06
17088.00	122.40	1.55	12.25	801.89	18.23	17104.50	130.74	0.98	9.14	801.89	21.89
17088.50	120.95	9.67	20.14	801.89	18.66	17105.00	129.90	6.09	12.24	801.89	20.74
17089.00	120.46	13.67	17.52	801.89	16.79	17105.50	129.71	9.01	17.85	801.89	20.68
17089.50	122.09	1.43	15.02	801.89	15.53	17106.00	129.73	9.35	13.48	801.89	21.80
17090.00	122.66	4.20	12.13	802.37	14.78	17106.50	128.43	20.61	15.58	801.89	21.94
17090.50	110.40	27.10	16.89	802.84	15.12	17107.00	130.09	2.09	12.36	802.84	22.56
17091.00	123.20	6.02	10.66	802.84	14.82	17107.50	131.97	0.35	19.47	803.08	22.52
17091.50	120.42	18.17	13.76	801.89	14.68	17108.00	129.90	8.78	14.40	801.89	16.01
17092.00	121.70	8.34	18.08	801.89	14.90	17108.50	129.20	12.66	16.09	801.89	16.21
17092.50	122.68	1.11	16.88	802.84	14.56	17109.00	129.94	8.26	8.66	801.89	17.07
17093.00	122.09	4.10	15.89	801.89	13.86	17109.50	130.59	1.81	11.38	802.84	17.73
17093.50	122.04	1.57	15.84	802.84	13.08	17110.00	130.90	1.28	11.11	802.84	17.41
17094.00	119.78	21.14	18.81	801.89	15.13	17110.50	128.54	13.10	10.71	801.89	17.38
17094.50	125.33	1.05	18.61	802.84	16.74	17111.00	131.38	1.41	13.95	801.89	17.57
17095.00	120.63	13.44	13.68	801.89	18.12	17111.50	131.01	0.57	10.50	801.89	17.05
17095.50	121.61	5.08	12.25	801.89	17.89	17112.00	130.01	6.29	7.44	801.89	14.00

17096.00	121.40	7.46	16.01	801.89	17.62	17112.50	129.82	6.64	6.83	801.89	12.81
17113.00	129.69	7.05	6.06	801.89	15.79	17129.50	126.10	7.33	7.32	801.89	17.33
17113.50	122.23	29.35	4.62	801.89	15.25	17130.00	138.23	18.52	12.89	802.37	17.76
17114.00	128.45	16.05	12.57	802.37	15.62	17130.50	140.32	6.54	4.50	801.89	14.27
17114.50	129.13	6.92	7.59	802.84	15.49	17131.00	139.70	8.51	10.16	801.89	15.08
17115.00	128.75	14.57	8.52	802.84	15.98	17131.50	138.38	18.95	7.21	801.89	16.15
17115.50	128.79	17.61	11.12	802.84	15.38	17132.00	138.85	14.81	6.60	801.89	16.42
17116.00	129.47	9.91	9.30	801.89	14.40	17136.50	139.54	9.11	11.42	801.89	15.72
17116.50	129.45	10.06	3.21	802.84	14.72	17137.00	139.85	7.36	9.98	802.37	15.33
17117.00	125.35	26.90	5.85	802.84	17.17	17137.50	140.17	7.90	12.94	801.89	14.25
17117.50	129.75	5.19	6.93	802.84	17.62	17138.00	140.30	6.65	9.80	801.89	13.67
17118.00	130.03	5.35	5.49	801.89	17.84	17138.50	139.92	7.63	11.93	802.84	13.58
17118.50	128.98	10.91	6.21	802.37	18.47	17139.00	139.53	9.56	12.42	801.89	13.24
17119.00	139.04	6.27	8.61	802.84	16.24	17139.50	140.32	2.28	6.88	801.89	13.14
17119.50	139.07	5.34	5.31	802.37	15.59	17140.00	139.13	10.95	6.06	802.37	13.23
17120.00	140.39	1.02	2.31	801.89	15.85	17140.50	139.83	11.93	7.93	802.37	14.59
17120.50	140.90	2.04	7.11	802.84	15.66	17141.00	140.71	2.66	1.44	802.84	15.51
17121.00	136.69	24.68	3.66	801.89	14.69	17142.50	139.36	11.84	4.45	801.89	18.57
17121.50	140.18	0.22	2.42	801.89	14.30	17143.00	140.65	2.83	1.16	802.84	20.22
17122.00	139.23	9.25	9.65	803.32	14.76	17143.50	139.43	13.22	5.57	801.89	22.11
17122.50	16.92	30.68	8.03	802.37	15.49	17144.50	140.13	5.87	2.41	802.37	25.25
17123.00	138.83	8.31	4.21	801.89	14.01	17145.00	140.58	3.04	1.37	801.89	25.03
17123.50	139.09	9.83	3.25	801.89	13.60	17146.00	140.50	3.89	3.34	801.89	25.88
17124.50	138.96	11.29	5.21	802.84	15.20	17146.50	140.18	6.54	2.60	801.89	27.54
17125.00	139.53	6.00	4.45	801.89	14.71	17147.00	139.90	7.91	3.21	801.89	27.65
17125.50	138.60	15.24	1.54	801.89	15.60	17147.50	140.96	1.93	1.09	801.89	28.28
17126.00	139.49	6.97	3.91	801.89	16.06	17148.00	140.13	5.30	4.58	801.89	27.27
17126.50	139.47	6.87	10.30	801.89	15.46	17148.50	139.62	7.93	5.59	801.89	27.23
17127.00	126.66	3.67	5.10	802.37	15.08	17149.00	139.79	7.98	5.22	801.89	25.58
17127.50	127.02	0.78	1.87	801.89	15.83	17149.50	140.80	2.74	3.53	802.37	26.30
17128.00	126.27	6.35	2.19	801.89	17.08	17150.00	140.30	5.69	7.63	802.37	25.35
17128.50	126.06	9.38	10.89	801.89	17.34	17150.50	132.40	16.78	12.74	801.89	22.46

17129.00	125.69	7.82	4.79	801.89	17.82	17151.00	139.39	14.28	8.80	801.89	21.59
17151.50	141.03	1.51	5.46	802.84	22.79	17168.00	139.96	6.35	11.95	801.89	16.58
17152.00	139.85	6.35	2.47	801.89	21.32	17168.50	140.26	5.34	7.13	801.89	19.71
17152.50	139.88	7.01	7.38	802.37	20.67	17169.00	140.28	7.39	12.71	802.37	18.85
17153.00	139.86	6.48	9.08	801.89	20.80	17169.50	139.24	12.69	19.33	801.89	19.88
17153.50	140.09	9.18	13.26	801.89	18.60	17170.00	139.71	7.37	20.11	801.89	22.44
17154.00	140.03	10.49	14.50	802.37	17.92	17170.50	139.96	6.60	14.96	801.89	25.11
17154.50	140.22	2.73	8.55	802.84	17.14	17171.00	139.56	10.12	14.41	802.37	25.76
17155.00	139.90	7.02	11.36	801.89	16.14	17171.50	139.68	8.43	14.80	801.89	26.18
17155.50	139.90	8.48	9.76	802.37	15.89	17172.00	139.58	8.67	14.98	801.89	26.81
17156.00	140.28	3.10	10.34	802.37	15.19	17172.50	138.29	15.75	11.31	801.89	26.99
17156.50	140.20	7.08	8.37	801.89	14.79	17173.00	140.35	4.00	4.46	801.89	27.14
17157.00	140.02	7.17	6.90	801.89	15.40	17173.50	140.02	7.58	9.62	801.89	26.61
17157.50	140.24	7.61	14.43	802.37	15.60	17174.00	139.70	7.51	8.77	801.89	28.01
17158.50	139.81	6.80	13.33	801.89	14.48	17174.50	140.24	7.63	17.07	801.89	26.50
17159.00	139.77	7.19	11.34	801.89	14.11	17175.00	139.36	10.86	17.21	801.89	29.07
17159.50	139.73	7.49	17.79	801.89	13.88	17175.50	139.60	10.47	19.48	801.89	28.15
17160.00	139.81	8.06	19.82	801.89	13.93	17176.00	139.36	9.89	18.81	801.89	27.43
17160.50	139.47	10.01	18.19	801.89	13.60	17176.50	140.11	6.32	14.50	801.89	23.41
17161.00	139.86	6.45	18.65	801.89	14.02	17177.00	140.33	6.97	14.86	801.89	20.52
17161.50	139.83	6.18	12.45	801.89	12.76	17177.50	139.92	8.19	17.80	801.89	18.04
17162.00	140.47	6.36	10.18	801.89	12.12	17178.00	139.49	8.13	18.40	802.37	17.02
17162.50	139.73	7.39	17.54	801.89	11.83	17178.50	140.49	3.04	9.44	801.89	16.98
17163.00	139.70	7.83	19.39	801.89	12.30	17179.00	139.60	8.43	11.06	801.89	18.00
17163.50	139.83	6.88	18.96	801.89	12.12	17179.50	138.23	22.28	11.58	802.84	18.24
17164.00	139.43	9.10	19.11	801.89	12.77	17180.50	140.15	7.61	13.45	801.89	16.59
17164.50	139.73	6.68	19.00	801.89	12.89	17181.00	139.92	6.02	16.52	802.37	16.75
17165.00	139.86	6.91	18.23	801.89	12.34	17181.50	139.32	8.94	13.19	802.84	19.05
17165.50	140.60	3.70	17.75	802.37	12.76	17182.00	139.64	9.17	16.25	801.89	19.93
17166.00	140.26	0.02	12.74	802.84	13.08	17182.50	139.79	7.76	21.94	801.89	22.31
17166.50	139.68	8.79	12.93	801.89	14.24	17183.00	140.07	8.04	24.95	801.89	21.96
17167.00	140.41	1.60	10.87	801.89	15.28	17183.50	140.02	7.15	19.07	801.89	19.08

17167.50	139.34	14.58	12.45	802.37	16.12	17184.00	139.28	12.64	19.12	801.89	16.76
17184.50	139.96	12.80	17.22	801.89	12.96	17201.50	140.47	5.52	11.82	801.89	14.54
17185.00	139.96	6.84	19.49	801.89	11.54	17202.00	139.49	9.44	15.48	801.89	13.47
17185.50	139.66	8.19	21.08	801.89	10.05	17202.50	139.79	7.22	13.84	801.89	13.48
17186.00	140.77	6.16	18.64	801.89	9.29	17203.00	139.58	12.43	13.40	801.89	13.36
17186.50	138.25	20.94	19.63	801.89	9.22	17203.50	139.92	8.40	12.47	801.89	13.34
17187.00	140.18	6.67	13.45	801.89	9.07	17204.00	139.94	8.35	11.06	801.89	14.66
17187.50	123.77	8.14	19.76	801.89	8.91	17204.50	142.06	27.65	15.05	802.84	16.01
17188.00	108.73	15.34	13.17	802.84	9.31	17205.00	147.93	18.10	16.62	802.37	17.05
17188.50	140.47	5.44	12.29	801.89	9.25	17205.50	146.97	24.16	14.74	803.08	17.03
17189.00	140.02	12.21	17.85	801.89	9.82	17206.00	149.94	3.58	15.28	801.89	16.51
17189.50	140.43	4.11	18.34	801.89	11.72	17206.50	149.02	8.53	9.52	801.89	18.45
17190.00	141.61	6.11	13.24	802.37	12.99	17207.00	149.19	6.54	8.11	801.89	19.21
17190.50	140.39	1.97	21.80	802.84	13.70	17207.50	138.68	18.10	15.82	801.89	20.22
17191.00	140.18	7.96	16.01	801.89	13.88	17208.00	141.39	2.73	11.78	801.89	22.98
17192.00	139.81	7.12	17.17	801.89	9.75	17208.50	149.38	8.46	18.05	803.08	21.96
17192.50	139.85	6.75	19.41	801.89	9.67	17209.00	149.47	5.41	15.70	802.84	21.63
17193.00	141.01	4.75	13.60	802.37	9.06	17209.50	147.31	16.06	16.24	802.37	23.81
17193.50	138.21	12.73	15.64	803.08	9.47	17210.00	149.49	6.23	12.74	801.89	28.92
17194.50	139.68	12.17	13.52	802.37	9.51	17210.50	140.00	6.75	15.78	801.89	24.67
17195.00	142.23	9.77	4.42	801.89	9.63	17211.00	139.64	8.42	21.24	802.37	20.76
17195.50	148.83	9.89	9.57	801.89	10.82	17211.50	140.32	6.77	16.02	801.89	14.88
17196.00	148.65	15.28	11.45	801.89	11.95	17212.00	140.17	8.05	19.43	801.89	10.28
17196.50	148.82	7.61	7.28	801.89	15.55	17212.50	138.79	9.92	16.64	802.84	9.53
17197.00	147.50	17.52	18.68	802.37	21.33	17213.00	149.44	7.14	19.88	802.37	8.83
17197.50	148.74	7.94	16.78	802.37	21.88	17213.50	139.30	10.54	15.55	801.89	8.22
17198.00	139.79	7.98	20.09	801.89	23.61	17214.00	140.15	6.12	15.03	801.89	7.25
17198.50	140.88	0.37	14.73	801.89	24.81	17214.50	151.00	2.36	15.99	801.89	6.68
17199.00	140.07	8.75	17.68	801.89	21.43	17215.00	150.24	6.20	14.76	801.89	5.98
17199.50	139.92	6.01	15.60	801.89	18.45	17215.50	150.04	7.05	15.97	801.89	6.03
17200.00	139.56	9.27	15.89	802.37	15.52	17216.00	140.32	6.64	15.61	801.89	6.01
17200.50	138.34	21.03	16.47	802.84	15.99	17217.00	151.03	1.19	18.87	802.84	8.16

17201.00	137.44	20.10	13.21	802.84	16.16	17217.50	151.30	1.99	15.85	802.84	7.98
17218.00	151.00	0.06	15.54	802.84	8.29	17234.50	149.64	4.59	10.11	792.11	11.90
17218.50	151.09	0.02	13.18	802.84	8.91	17235.00	147.80	16.13	16.51	791.87	11.19
17219.00	151.13	0.32	8.75	802.84	9.01	17235.50	150.23	2.77	7.37	792.35	11.01
17219.50	150.39	8.23	17.58	801.89	9.37	17236.00	149.76	8.22	5.98	791.63	9.91
17220.00	150.23	7.02	17.61	802.37	10.93	17236.50	148.98	8.32	10.66	792.11	9.73
17220.50	139.00	14.15	16.03	802.37	10.56	17237.00	149.36	6.58	12.48	792.35	9.96
17221.00	150.56	0.90	17.80	801.89	11.53	17237.50	149.45	7.75	15.67	792.35	9.89
17221.50	148.93	10.18	22.18	802.84	11.50	17238.00	149.19	7.15	10.83	792.35	9.05
17222.00	149.57	5.92	19.97	802.84	11.56	17238.50	148.82	10.44	18.12	792.35	8.88
17222.50	150.38	0.55	14.41	802.84	12.15	17239.00	150.92	0.28	11.53	792.11	9.64
17223.00	150.58	0.73	12.22	802.84	12.05	17239.50	149.85	6.40	21.22	792.35	9.47
17223.50	149.57	4.10	13.96	801.89	11.98	17240.00	149.64	5.52	14.85	791.87	9.00
17224.00	149.94	3.27	12.52	801.89	14.27	17240.50	149.12	7.88	17.84	791.63	8.60
17224.50	150.00	0.20	16.84	801.89	15.47	17241.00	149.32	8.71	16.07	792.11	8.73
17225.00	149.62	6.39	15.54	801.89	15.39	17241.50	149.70	8.19	18.29	791.87	7.97
17225.50	149.21	9.00	18.06	802.37	16.90	17242.00	148.10	15.15	25.64	792.35	7.93
17226.00	149.66	6.40	16.31	802.37	16.19	17242.50	149.49	7.79	15.14	791.87	5.23
17226.50	148.63	14.40	17.39	802.37	18.05	17243.00	149.55	8.25	18.01	791.87	4.87
17227.00	148.68	10.31	17.06	802.84	18.14	17244.50	149.08	9.34	25.04	791.63	5.05
17227.50	148.97	8.36	20.29	802.37	18.22	17245.00	149.10	8.74	25.09	791.63	5.17
17228.00	148.82	12.60	18.53	801.89	18.51	17245.50	149.81	7.03	20.32	789.49	5.32
17228.50	150.08	3.16	12.46	801.89	19.07	17246.00	149.68	8.72	25.82	792.11	5.41
17229.00	149.21	7.79	17.39	802.37	20.54	17246.50	149.38	6.22	18.52	791.87	5.41
17229.50	148.59	8.46	20.88	802.84	20.21	17247.00	149.83	5.98	19.80	792.11	4.69
17230.00	149.25	6.20	14.65	802.84	21.08	17247.50	110.46	4.09	7.55	602.73	2.80
17230.50	148.36	13.51	15.34	801.89	20.37	17248.00	109.50	12.10	18.97	602.73	2.63
17231.00	148.57	12.27	20.62	801.89	21.60	17248.50	118.26	15.10	14.70	603.21	2.61
17231.50	148.51	12.91	13.14	801.89	21.52	17249.00	138.79	13.77	5.44	602.73	2.51
17232.50	139.02	6.92	14.38	791.87	18.73	17249.50	149.19	7.91	15.48	603.21	2.33
17233.00	140.13	5.00	18.87	791.87	18.83	17250.00	149.34	6.70	10.00	602.73	2.36
17233.50	138.70	14.35	15.92	792.11	17.00	17250.50	151.77	0.99	13.66	602.73	2.35

17234.00	149.04	12.59	15.06	791.87	12.90	17251.00	139.38	7.25	18.15	602.73	2.34
17251.50	139.86	1.95	12.74	602.73	2.28	17271.00	137.97	15.38	17.62	603.21	11.67
17252.00	148.16	16.57	16.81	603.21	2.44	17271.50	137.91	18.35	19.38	603.21	11.59
17252.50	140.33	6.83	16.81	602.73	4.34	17272.00	137.44	20.30	29.30	602.73	13.66
17253.00	139.47	10.71	24.57	602.73	5.26	17272.50	137.50	17.37	28.91	603.21	13.97
17253.50	140.43	6.35	20.26	602.73	4.97	17273.00	138.38	8.49	27.74	603.21	12.87
17254.00	140.43	7.50	18.33	595.34	4.85	17274.00	144.11	9.30	23.18	603.21	13.67
17254.50	140.02	5.84	19.96	602.73	5.11	17274.50	145.98	0.81	23.56	603.21	11.90
17255.00	149.08	8.48	24.02	602.73	4.68	17275.00	143.42	22.47	25.44	602.73	10.85
17255.50	149.38	10.62	33.37	602.73	4.32	17275.50	138.42	22.21	24.64	602.97	10.86
17258.50	100.17	4.41	11.27	602.73	24.48	17276.00	148.14	1.03	30.41	602.73	10.79
17259.00	100.09	7.05	12.03	602.73	13.42	17276.50	147.99	0.83	27.15	603.21	10.57
17259.50	139.94	8.38	22.03	602.73	10.67	17277.00	139.56	30.54	31.71	602.73	9.13
17260.00	140.18	7.20	17.39	602.73	5.78	17277.50	145.81	20.33	27.98	602.73	9.47
17260.50	140.02	7.63	25.37	602.73	5.46	17278.00	145.66	22.03	30.57	602.73	9.30
17261.00	151.18	0.64	27.11	602.73	8.30	17278.50	140.39	27.22	25.15	602.73	10.54
17262.00	129.41	17.29	27.76	603.21	7.76	17279.00	148.01	5.40	29.02	602.73	10.75
17262.50	128.21	24.80	26.85	603.21	7.40	17279.50	148.33	9.17	34.53	595.34	11.81
17263.00	131.82	0.26	27.86	603.21	6.91	17280.00	146.65	8.41	32.52	602.73	12.15
17263.50	132.06	1.72	28.53	603.21	6.81	17280.50	146.46	15.05	32.91	602.73	12.82
17264.00	147.69	17.36	30.16	598.20	6.55	17281.00	148.80	1.21	22.81	602.73	12.58
17264.50	150.60	1.35	29.43	603.21	6.62	17281.50	146.35	18.83	25.25	602.01	12.12
17265.00	138.38	11.00	27.30	603.21	7.32	17282.00	148.89	0.55	28.89	595.57	13.46
17265.50	139.81	1.01	24.76	603.21	7.83	17282.50	145.71	0.70	24.37	602.73	11.94
17266.00	138.62	18.37	26.11	603.21	7.55	17283.00	145.34	2.86	28.77	602.73	11.87
17266.50	140.56	0.49	28.53	603.21	10.20	17283.50	142.67	22.64	31.51	602.73	10.72
17267.00	149.36	5.50	29.93	595.81	10.23	17284.00	140.82	5.92	30.17	602.73	10.06
17267.50	137.66	18.40	32.08	603.21	10.06	17284.50	140.41	0.36	26.03	602.73	9.79
17268.00	150.85	8.35	28.32	603.21	10.85	17285.00	138.17	21.72	27.56	602.49	8.44
17269.00	140.07	4.58	15.06	602.97	10.13	17286.00	138.83	0.01	25.31	602.01	8.59
17269.50	138.40	19.00	8.70	602.97	10.88	17286.50	136.24	0.81	24.10	602.49	8.20
17270.00	137.53	24.62	19.20	603.21	12.02	17287.00	141.01	1.55	27.85	602.73	7.71

17270.50	138.17	10.75	2.32	603.21	10.77	17287.50	141.59	1.46	28.56	602.73	7.88
17288.00	143.44	12.88	28.26	602.73	8.41	17304.50	140.11	5.86	29.28	603.21	5.39
17288.50	143.46	20.48	27.32	602.73	8.19	17305.00	139.43	11.20	28.04	602.73	3.78
17289.00	133.85	18.42	34.76	602.73	8.26	17305.50	139.88	6.72	34.21	602.73	3.70
17289.50	134.99	6.38	28.53	602.73	7.32	17306.00	149.40	7.02	36.70	602.73	3.55
17290.00	142.12	4.19	27.94	602.01	7.27	17306.50	140.17	1.07	30.31	602.97	3.34
17290.50	139.56	18.80	32.74	602.73	5.84	17307.00	138.92	3.81	28.69	602.73	3.41
17291.00	139.79	20.50	30.88	602.73	5.85	17307.50	137.95	13.15	31.16	603.21	3.01
17291.50	141.71	0.70	27.10	602.73	5.57	17308.00	139.00	17.56	37.76	603.21	3.04
17292.00	141.18	10.34	32.67	602.73	4.95	17308.50	138.27	21.27	36.30	603.21	3.03
17292.50	140.22	8.44	28.91	602.73	4.74	17309.50	129.71	7.02	23.26	595.10	3.13
17293.00	131.87	18.94	28.77	602.73	4.21	17310.00	138.89	7.20	25.85	602.73	3.50
17293.50	147.76	18.40	27.34	603.21	4.23	17310.50	124.16	1.45	18.41	603.21	2.95
17294.00	141.54	0.07	16.00	603.21	3.68	17311.00	130.22	3.98	21.27	603.21	2.92
17294.50	141.31	0.35	12.49	595.57	3.81	17311.50	130.22	4.66	25.41	602.73	2.93
17295.00	150.11	0.61	13.36	603.21	3.32	17312.00	138.66	9.81	27.38	603.21	3.07
17295.50	139.86	0.76	7.97	603.21	3.00	17312.50	138.83	7.99	28.84	602.73	3.21
17296.00	140.45	0.62	21.48	603.21	3.05	17313.00	138.92	8.01	28.34	602.73	3.26
17296.50	139.88	5.39	19.55	603.21	3.12	17313.50	129.75	6.61	33.00	602.73	2.98
17297.00	137.66	20.46	25.00	602.73	3.47	17314.00	149.14	10.82	31.93	602.73	3.07
17297.50	139.68	3.32	20.99	602.97	3.36	17314.50	150.53	1.26	29.91	603.21	3.08
17298.00	139.24	3.20	24.63	595.34	3.65	17315.00	150.06	5.07	28.65	603.21	3.44
17298.50	148.65	17.52	23.65	603.21	3.68	17316.00	140.05	11.29	37.12	602.97	4.04
17299.00	146.63	28.90	24.69	602.73	4.41	17316.50	129.73	8.05	32.10	602.97	4.35
17299.50	148.51	12.60	21.76	603.21	4.69	17317.00	150.30	2.79	31.04	602.73	4.24
17300.00	149.77	3.06	20.26	602.73	6.59	17317.50	148.68	8.50	29.02	603.21	4.52
17300.50	150.15	1.14	23.24	603.21	11.57	17318.00	129.77	8.88	35.01	602.73	4.09
17301.00	147.61	18.92	33.28	602.97	9.50	17318.50	129.75	7.51	30.29	602.73	4.63
17301.50	150.23	1.28	25.04	602.97	10.12	17319.00	119.74	7.70	37.42	602.73	3.57
17302.00	149.98	1.18	28.26	602.73	7.72	17319.50	118.60	15.21	36.43	602.73	3.40
17303.00	147.69	16.38	39.15	603.21	7.47	17320.00	147.59	20.86	39.99	595.81	3.17
17303.50	147.57	17.45	32.81	597.96	7.43	17320.50	149.30	5.19	34.12	603.21	3.07

17304.00	139.81	0.53	29.50	599.15	6.30	17321.00	151.15	1.07	32.49	603.21	2.85
17321.50	149.17	9.95	41.26	603.21	2.73	17338.50	150.32	10.05	41.65	602.73	1.54
17322.00	129.47	13.05	41.79	602.73	2.81	17339.00	138.38	15.88	43.31	603.21	1.87
17322.50	129.97	5.04	33.56	603.21	2.56	17339.50	140.17	12.24	42.09	602.73	1.92
17323.00	147.97	17.85	38.82	603.21	2.69	17340.00	134.67	8.46	40.49	602.73	1.94
17323.50	150.77	1.13	31.96	603.21	2.54	17340.50	134.81	6.77	44.90	595.57	1.81
17324.00	100.64	0.42	27.72	603.21	2.79	17341.00	145.17	4.95	37.83	603.21	2.13
17324.50	80.11	2.88	38.29	603.21	2.53	17341.50	149.44	10.76	41.92	602.73	2.08
17325.00	78.83	10.67	37.46	602.97	2.69	17342.00	140.45	7.65	42.81	602.73	2.15
17325.50	100.09	3.66	33.61	602.73	2.39	17342.50	140.30	9.47	42.88	602.73	2.00
17326.00	128.24	18.37	35.67	602.97	2.55	17343.00	134.73	11.08	42.95	602.73	1.91
17326.50	138.64	10.52	41.29	602.73	2.47	17343.50	134.56	10.49	46.57	602.73	1.72
17327.00	149.47	6.51	33.98	602.73	2.39	17344.00	139.07	10.83	40.23	602.73	1.70
17327.50	129.69	7.59	41.59	602.97	2.50	17344.50	150.32	0.10	36.77	602.73	1.49
17328.00	119.20	11.04	36.38	602.97	2.41	17345.50	58.80	9.02	41.99	603.21	1.42
17328.50	130.41	4.60	34.60	602.73	2.60						
17329.00	147.93	21.73	41.86	602.73	2.51						
17329.50	148.51	14.31	32.67	595.34	2.78						
17330.00	149.25	10.83	37.21	602.73	2.82						
17330.50	149.55	9.13	37.51	602.97	3.42						
17331.00	129.86	5.41	36.63	594.86	3.73						
17331.50	109.91	5.13	36.10	602.73	3.80						
17332.00	99.27	11.20	28.16	602.73	2.49						
17333.00	109.36	6.54	41.33	602.73	2.34						
17333.50	130.07	6.05	40.23	602.73	2.15						
17334.00	129.97	8.50	45.99	602.73	1.71						
17334.50	125.03	7.22	37.42	597.96	1.70						
17335.00	125.03	7.82	47.34	602.73	1.62						
17335.50	129.82	8.29	46.56	595.57	1.53						
17336.00	139.24	6.43	37.71	602.73	1.30						
17336.50	138.85	7.77	32.22	602.73	1.29						