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Analysis of the challenges and solutions to boost operational performance of exploratory wells in the Brazilian pre-salt oil fields

São Paulo
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Corrected Version

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Concentration area:
Mineral Engineering

Supervisor:
Giorgio de Tomi

Co-supervisor:

São Paulo
2023

Este exemplar foi revisado e corrigido em relação à versão original, sob
responsabilidade única do autor e com a anuência de seu orientador.

Assinatura do autor: ______________________________

Assinatura do orientador: ______________________________

Catalogação-na-publicação

Ribeiro, Rodrigo Rodrigues
Analysis of the challenges and solutions to boost operational performance of exploratory wells in the Brazilian pre-salt oil fields / R. R. Ribeiro -- versão corr. -- São Paulo, 2023.
65 p.

Dissertação (Mestrado) - Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia de Minas e de Petróleo.

1.OLEO e GÁS 2.PETRÓLEO 3.PERFURAÇÃO DE POÇOS 4.PERFURAÇÃO MARÍTIMA I.Universidade de São Paulo. Escola Politécnica. Departamento de Engenharia de Minas e de Petróleo II.t.

Nome: RIBEIRO, Rodrigo Rodrigues

Título: Impulsionando Desempenho Superior no Pré-sal Brasileiro - Os Desafios, Soluções e Conquistas em Poços Exploratórios do Pré-Sal no Brasil.

Dissertação apresentada à Escola Politécnica da Universidade de São Paulo para obtenção dotítulo de Mestre em Ciências.

Aprovado em:

Banca Examinadora

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Instituição: ____

Julgamento: ____

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Julgamento: ____

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RESUMO

RIBEIRO, R. R. **Análise dos desafios e soluções para aprimorar o desempenho operacional de poços de exploração no Pré-Sal Brasileiro**. 2023. Dissertaçao (Mestrado) – Escola Politécnica, Departamento de Engenharia de Minas e de Petroleo, Universidade de São Paulo, São Paulo, 2023.

Esta dissertação apresenta uma análise abrangente da bem-sucedida campanha de perfuraçao conduzida pelo operador e companhia de perfuração (Drilling Contractor) na região do Pré-Sal brasileiro, onde quatro poços pré-sal foram perfurados. A parceria entre a companhia de perfuração, operador e o provedor de serviços de perfuração de poços desempenhou um papel significativo no sucesso da campanha. A metodologia de Pacote de Plataforma de Perfuração, Pacote de Serviço Integrado, Serviços Adquiridos Diretamente, Planejar, Executar e Verificar (DID-PDCA - sigla em ingles), promove a melhoria cont´ınua do proceso de perfuração de poço, foi utilizada para aprimorar a integração entre a força de trabalho. A campanha bem-sucedida resultou na obtenção de quatro poços de classe mundial (Best-in-Class - BIC), situados dentro do percentil dos 5 por cento melhores poços do pré-sal. Em 2019, o poço GdM3 foi a entrega mais rápida de um poço no pré-sal entre os mais de 250 poços na região. O poço GdM4 perfurado em 2020, como parte da mesma campanha, quebrou o recorde anterior em sete dias, sendo o poço do pré-sal mais rápido já perfurado, com um tempo de 18 dias . A metodologia de pesquisa empregada neste estudo é descritiva, e os achados apresentados têm implicações significativas para a indústria de perfuração, onde operações de perfuração seguras e eficientes são cruciais para a redução de custos e aumento da produtividade. Esta dissertação aborda os principais desafios encontrados na exploração do pré-sal, juntamente com as estratégias empregadas para superá-los. Destaca os métodos utilizados para reduzir o tempo de perfuração e enfatiza os fatores-chave que contribu´ıram para o sucesso geral da campanha conduzida pelas três partes. Isso inclui a implementação da metodologia DID-PDCA e a colaboração entre o companhia de perfuração offshore, operador e provedor de serviços de perfuração de poços.

Palavras-Chave – Exploração, Pré-Sal, operações de perfuração, metodologia DID-PDCA.

ABSTRACT

RIBEIRO, R. R. **Analysis of the challenges and solutions to boost operational performance of exploratory wells in the Brazilian pre-salt oil fields**. 2023. Dissertação (Mestrado) – Escola Politécnica, Departamento de Engenharia de Minas e de Petróleo, Universidade de São Paulo, São Paulo, 2023.

This dissertation presents a comprehensive analysis of the successful drilling campaign conducted by operator and drilling contractor in the Brazilian Pre-Salt region, where four pre-salt wells were drilled. The partnership between the drilling contractor, operator, and the well drilling service provider, played a significant role in the campaign's success. The DID-PDCA methodology which stands for Drilling rig package, Integrated service package, Directly procured services, Plan, Do and Check, promotes continuous improvement, was utilised to enhance integration among the workforce. The successful campaign resulted in the achievement of four best-in-class (BIC) wells, which is within the top 5 percentile. In 2019, the GdM3 well was the fastest delivery of a pre-salt well out of the 250+ wells in the region. The well GdM4 drilled in 2020 as part of the same campaign, broke the previous record by seven days, being the fastest pre-salt well ever drilled, with an 18 dry hole days mark. The research methodology employed in this study is descriptive, and the presented findings have significant implications for the drilling industry, where safe and efficient drilling operations are crucial for cost reduction and improved productivity. This dissertation covers the main challenges encountered in the pre-salt exploration, along with the strategies employed to overcome them. It highlights the methods used to reduce drilling time and emphasizes key factors that contributed to the overall success of the campaign conducted by the three parties. These include the implementation of the DID-PDCA methodology and the collaboration between the contractor, operator, and well drilling service provider. .

Keywords – Exploration, Pre-salt, drilling operations, DID-PDCA methodology.

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LIST OF ACRONYMS

A&A - Assist and Assure

API - American Petroleum Institute

BHA - Bottom Hole Assembly

DID - Drilling rig package, Integrated service package, Directly procured services

DGMCD - Dual Gradient Drilling with Mud Cap Drilling

DWOP - Drilling Well On Paper

GOR - Gas Oil Ratio

H2S - Hydrogen Sulfide

HSE - Health, Safety, and Environment

KPI - Key Performance Indicator

MPD - Managed Pressure Drilling

NPT - Non-Productive Time

PDCA - Plan, Do, Check, Act

RIH - Run In Hole

RM - Risk Management

ROP - Rate of Penetration

RTOC - Real-Time Operations Center

SBPSC - Santos Basin pre-salt cluster

WAG - Water Alternating Gas

WOB - Weight on Bit

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1 INTRODUCTION

1.1 Research Background

The Brazilian Pre-Salt region has been recognized as a world-class province with its prolific production and technical challenges. With its huge reserves of hydrocarbons, the pre-salt layer represents a significant opportunity for the oil and gas industry (Da Costa Fraga et al., 2015). However, drilling operations in this challenging environment requires advanced technology and expertise, as well as an integrated approach to mitigate risks and improve performance.

Several companies have invested in the exploration and production of the pre-salt layer, and many have faced significant technical challenges in the process (Azevedo et al., 2010). These challenges include high pressures, high temperatures, and complex geology, which can lead to drilling difficulties, lost time, and increased costs. Additionally, safety is a major concern in this industry, and any accidents or incidents can have severe consequences for the environment, the workforce, and the company's reputation (De Souza & Werneck, 2015).

To address these challenges, the market has been seeking safer and more efficient approaches to drilling operations. This has led to the development of new technologies and processes, as well as an increased emphasis on collaboration and integration among different stakeholders. Companies are also adopting various management systems, such as the Plan-Do-Check-Act (PDCA) methodology, to promote continuous improvement and enhance performance. In this context, the successful drilling campaign conducted by Operator and Drilling contractor in the Brazilian Pre-Salt region represents a significant achievement. The campaign involved the drilling of four pre-salt wells and resulted in the achievement of best-in-class drilling times. The partnership between the drilling contractor, operator, and main services provider, Well drilling service provider, played a significant role in the campaign's success. The DID-PDCA methodology, which promotes continuous improvement, was utilised to enhance integration among the workforce.

This dissertation aims to provide valuable insights and comprehensive description of the successful drilling campaign conducted by Operator and Drilling contractor in the Brazilian Pre-Salt region, where four pre-salt wells were drilled. The presented findings have significant implications for the drilling industry, where safe and efficient drilling operations are crucial for cost reduction and improved productivity. The general objective of this study is to investigate the challenges, solutions, and achievements in the exploratory campaign in the Brazilian Pre-Salt, and to draw lessons that may be useful for future pre-salt exploration wells in Brazil and other similar contexts.

1.2 Problem statement

Despite the Brazilian Pre-Salt region being recognized as a world-class province for its prolific production and technical challenges, drilling operations in this area have faced significant safety and efficiency challenges. To address these challenges, the industry has been seeking safer and more efficient approaches to drilling operations. Therefore, the problem statement of this research is to identify the essential factors that contributed to the successful drilling campaign conducted by the operator and drilling contractor in the Brazilian Pre-Salt region, where four pre-salt wells were drilled, with the goal of achieving best-in-class drilling times.

1.3 Research questions

The purpose of the research is to analyse the challenges, solutions, and achievements in the exploratory campaign in the Brazilian Pre-Salt and draw lessons that can be useful for future pre-salt exploration wells. The study aims to advance knowledge and understanding in the field of pre-salt exploration and may be of interest to stakeholders in the oil and gas industry. The research aims to answer the following questions:

1. What were the main challenges faced in exploratory campaign in the Brazilian Pre-Salt, and how were they overcome?
2. What strategies and techniques can be employed to reduce drilling time and improve efficiency in pre-salt exploration?
3. How can the implementation of the DID-PDCA methodology contribute to the success of drilling campaigns in the Brazilian Pre-Salt region?

1.4 Research Objectives

1. Identify the main technical challenges faced in the exploratory campaign in the Brazilian Pre-Salt.
2. To identify the strategies and techniques used to reduce drilling time in pre-salt exploration.
3. To assess the impact of implementing the DID-PDCA methodology on drilling campaign performance in the Brazilian Pre-Salt region.

1.5 Methodology

The research methodology employed in this dissertation is descriptive, which aims to provide an analysis of the successful drilling campaign conducted by Operator and Drilling contractor in the Brazilian Pre-Salt region. The study utilised a case study approach to gather data from various sources, including interviews with key personnel involved in the project and operational data. The DID-PDCA methodology was the primary tool utilised in the campaign to promote continuous improvement and enhance integration among the workforce. This methodology involves four main steps, namely Define, Implement, Deliver, and Plan. The Define phase focuses on identifying the problem or opportunity for improvement, while the Implement phase involves developing and implementing a plan to address the issue. The Deliver phase focuses on executing the plan, and the Plan phase involves monitoring and evaluating the results to identify areas for improvement continuously. The partnership between the drilling contractor, operator, and main services provider, Well drilling service provider, played a crucial role in the campaign's success. The study examined the various aspects of the partnership, including communication, collaboration, and resource allocation, to determine how they contributed to the project's success. The research methodology employed in this study serves as a framework for future studies in the drilling industry.

2 LITERATURE REVIEW

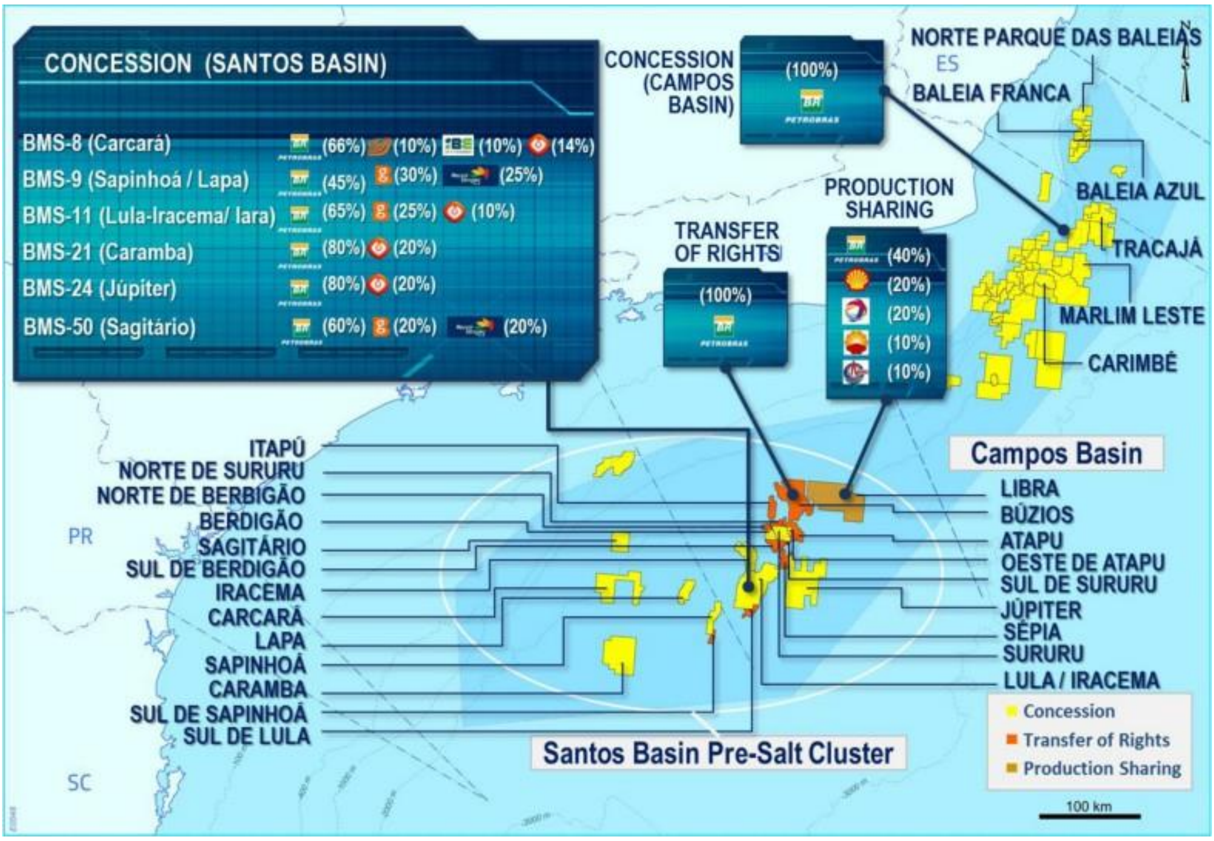
This chapter provides a comprehensive knowledge and research related to the exploration activities in the Brazilian pre-salt region. It serves as a foundation for understanding the current state of knowledge. The literature review begins by exploring the historical background of pre-salt exploration in Brazil, discussing key milestones, discoveries, and the overall importance of the pre-salt reserves. It then delves into the challenges of drilling operations within the pre-salt reservoirs. Providing this literature allows the readers to understand the context, significance, and relevance of the study and its contribution to the field of pre-salt exploration in Brazil.

2.1 Surmary of the Brazilian presalt

The term “pre-salt” refers to a geological formation found beneath layers of salt in offshore oil and gas reservoirs. It is called ”pre-salt” because the reservoirs are located beneath thick layers of salt deposits that were formed millions of years ago This Basin was formed when the continent split forming the African continent and the South American continent and the processes of the reservoir formation were triggered during the separation of the continents approximately 120 million years (Aptain age). The thick salt layer formed the ceiling of the reservoir (Carminatti et al., 2008). These reservoirs are typically found in deep-water basins and can hold significant amounts of hydrocarbon resources. The discovery of pre-salt, the enhancement of existing technologies and the creation of new ones for exploration and production development represented one of the biggest technological challenges of the Brazilian oil industry in the last decade. The Brazilian pre-salt is predominantly found mainly in the Santos and Campos Basins which are located along the south-eastern coast of Brazil. They have been the primary areas of interest and development and the primary focus of pre-salt exploration and production activities in Brazil.

Parati was the first exploration pre-salt well drilled in 2005 in the Santos Basin and in the following year, the Lula field was discovered with a whopping greater than 8500 million bbl. This led to the drilling of more than 70 wildcats in 2015. Several pre-salt plays has been discovered since then but the Lula field remains at the top. Libra and Franco field are next in ranking to the Lula field. As of 2015, according to ANP, the overall pre-salt discoveries amount to 30 billion bbl recoverable resource. After drilling the Parati well, an exploration concession BM-C-33 was initiated in 2006 which resulted in two oil discoveries Seat (To Be Confirmed) (2009-2010) and Gávea (2010-2011) followed by Pão de Açucar (PdA) in 2011-2012. Significant technological challenges were faced in the drilling of these wells with a -7036 m in total vertical depth subsea (TVDSS) (Luca et al, 2017). See the main pre-salt blocks of the Santos and Campos Basin in Figure 1

Figure 1: Pre-salt Cluster Areas in the Santos and Campos Basin



Source: Da Costa Fraga et al. 2015

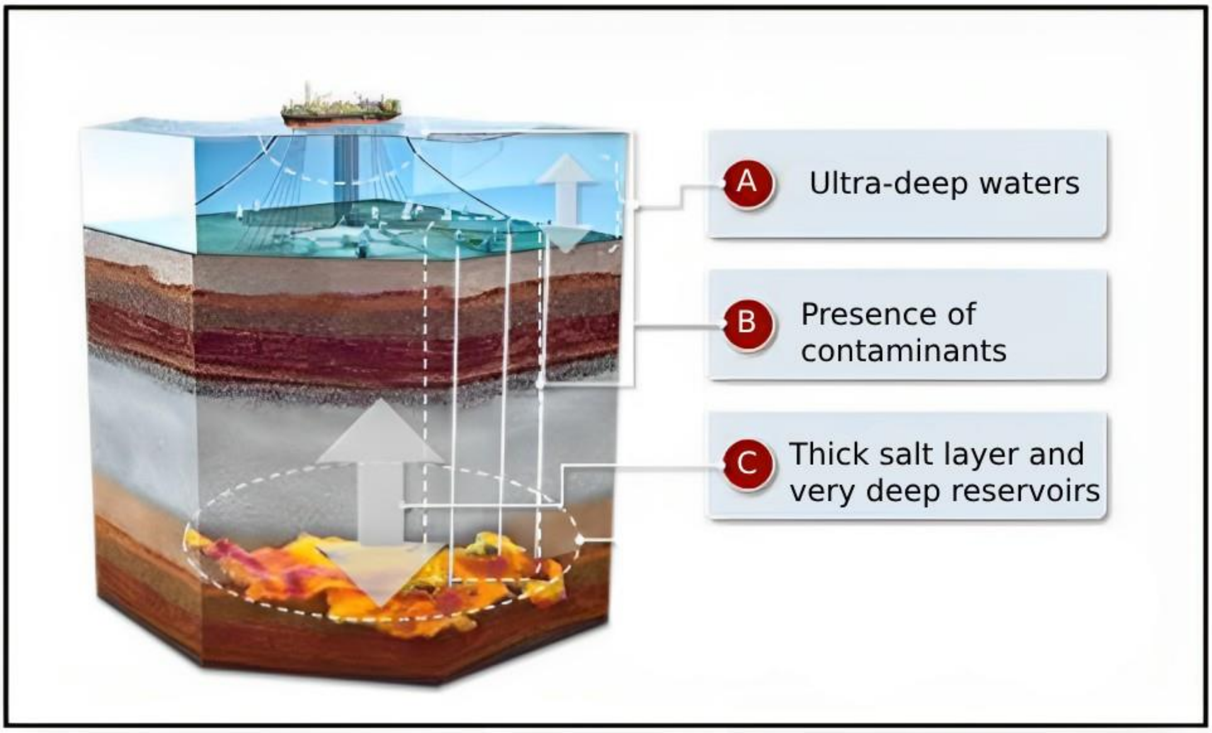
2.2 Main challenges in presalt exploration

The exploration of pre-salt reservoirs has emerged as a significant frontier in the oil and gas industry, presenting unique challenges and opportunities for successful hydrocarbon extraction. This subchapter delves into the main challenges encountered during pre-salt exploration, aiming to provide a comprehensive understanding of the technical, operational, and environmental obstacles faced by exploration teams. By examining these challenges, we can gain valuable insights into the complexities of working in ultra-deepwater environments, dealing with thick salt layers, heterogenous reservoirs, flow assurance issues, and the presence of contaminants. Understanding and effectively addressing these challenges is crucial for optimizing exploration strategies, enhancing safety and efficiency, and ultimately unlocking the vast potential of pre-salt reservoirs.

Pre-salt exploration presents unique and significant challenges in the oil and gas industry. These challenges arise from the complex geological characteristics and operational conditions associated with extracting hydrocarbon resources from reservoirs located deep beneath thick salt layers in offshore basins. By understanding and addressing these challenges, the industry can develop effective strategies to optimize exploration and production activities in pre-salt fields (Pinheiro et al., 2015).

The four wells that were drilled are located in the Santos Basin pre-salt cluster (SBPSC), the basin is located in ultra-deep waters offshore the Rio de Janeiro Coast, it is a continuous evaporitic sequence of greater than 2000 m with the pre-salt target of comprising of thick carbonate section that can be up to 6500 m (Da Costa Fraga et al., 2015). These reservoirs are exceptional and unmatched throughout the world in their attributes (Moczydlower et al., 2012). It was a completely new frontier hence various technological challenges were faced. The first challenge was that the reservoirs were in ultra deep waters, CO2 was present in the associated gas, flow assurance issues, the salt layer is very thick hence drilling through it was a big challenge, see Figure 2. Other pre-salt challenges include viscous-plasticity of the salt rock that is responsible for wellbore closure as a function of time, creating significant difficulties for well construction (Beltrao et al., 2009), the plastic behaviour of salt formations caused various issues such as the weakening of the wellbore wall, poor casing cementing, casing deformation, wellbore collapse, stuck pipe, drilling shock and vibration, and low Rates Of Penetration (ROP), ultimately driving up pre-salt-well construction costs, the heterogeneous nature of the of the microbial carbonate reservoir, the 2,000 m salt layer and drilling concerns associated, the compositional grading in the reservoir fluids, special demands concerning subsea engineering, well construction and processing plant. Figure 2 illustrates the main challenges of the presalt.

Figure 2: The complex scenario of the Brazilian pre-salt (sumary of the technical and logistic challenges)



Source: Moczydlower et al. 2012

A – Apart from the depth of the water there is a distance of around 300km from shore where there is no previous infrastructure.

B – The presence of CO2 and H2S contaminants in the reservoir pose the challenges of corrosion, they alter the viscosity, density and phase behaviour of the hydrocarbons affecting the flow rates and overall production performance. It also poses threats to Health, Safety and Environment (HSE).

C – Drilling through very variable thick layers of salt is challenging, the difficulty arise in the seismic illumination of the reservoirs.

There are also reservoir characterization and development challenges in Santos Basin Pre-salt Cluster (SBPSC) that were outlined by Moczydlower et al. (2012):

1. External geometry, internal barriers, and facies variations affecting reservoir connectivity
2. Rock types modeling and their association with petrophysical properties
3. Definition of static properties (porosity, saturation, net to gross ratio) and dynamic properties (permeability, relative permeability, capillary pressures)

4. Performance of water, gas, and WAG injection considering reservoir heterogeneity
5. Presence and impact of fractures on flow and sweep efficiency
6. Interaction between reservoir rock and injected fluids, considering carbonate reactivity
7. Compatibility of formation water with injected sea water, risk of scale precipitation
8. Composition and grading of CO2, API, GOR, and viscosity within the reservoir
9. Initial stress state, pore pressures, and mechanical properties of the salt layer
10. Flow assurance properties: low temperatures, wax appearance, rheological behavior, asphaltene and hydrate potential
11. Special Pressure-Volume-Temperature properties for gas injection: miscibility pressure, oil swelling for WAG (Water Alternating Gas) injection

The presence of these uncertainties significantly influences various aspects, including the design of well construction (geometry, metallurgy, and casing program), specification of risers and flow lines, configuration of fluid processing plants in production units, development of the drainage plan and recovery mechanisms, and even the ongoing reservoir management following initial oil production.

Bruhn et al. (2017) mentioned the Santos Basin pre-salt reservoir characterization faces challenges such as:

1. Complex 3D seismic velocity fields, interbedded seismic multiples, and complexity in geological facies and diagenesis of carbonates.
2. Low seismic resolution and ambiguity in acoustic impedance further complicate reservoir mapping and interpretation.
3. Elastic inversion results can be unstable, requiring specific data preconditioning and acquisition geometry for improved reliability.

The exploration of pre-salt reservoirs in the Santos Basin has revealed a multitude of challenges that must be addressed to maximize the potential of these exceptional hydrocarbon resources. This subchapter has provided a brief analysis of the main obstacles encountered during pre-salt exploration, including the complexities of working in ultra-deepwater environments, drilling through thick salt layers, managing flow assurance issues, and dealing with reservoir heterogeneity. The technical, operational, and environmental aspects have been thoroughly examined to gain a deeper understanding of the unique conditions associated with pre-salt fields. By highlighting these challenges, this subchapter emphasizes the importance of developing effective strategies and innovative technologies to optimize exploration and production activities in this frontier. Future efforts should focus on enhancing reservoir characterization, improving seismic imaging techniques, and implementing advanced monitoring systems to ensure safe and efficient operations. Only by overcoming these challenges can we fully unlock the immense potential of pre-salt reservoirs and secure a sustainable energy future.

2.3 Solutions and achievements

The exploration of pre-salt reservoirs has presented a multitude of challenges, ranging from complex geological formations to operational constraints in ultra-deepwater environments. However, these challenges have spurred innovation and the development of novel solutions to overcome them. This subchapter focuses on exploring the various solutions and achievements that have emerged in the field of pre-salt exploration. By analyzing successful case studies and technological advancements, we aim to highlight the strategies, technologies, and best practices that have enabled the industry to overcome the main challenges associated with pre-salt exploration. Understanding these solutions and achievements is essential for shaping future exploration strategies, optimizing resource recovery, and ensuring the sustainable development of pre-salt reserves.

Fernandes et al. (2020) addressed the pre-salt drilling-related challenges based on a literature review and discussed some key improvement opportunities, such as the use of nano-fluids and artificial intelligence (AI) to provide the reliability of drilling fluids selection aiming to make the whole drilling operation safer and minimise Non-Productive Time (NPT). Barcelos et al. (1993) addressed the main problems faced in the Campos Basin area, southeast Brazil, during the deep water exploratory program and the solutions achieved to solve them. The operational difficulties were overcome by the development of new equipment and procedures, the implementation of high standards of reliability and safety, and aiming to keep the operations as simple as possible. Constant optimization in all levels of operation brings local savings and solutions to drilling problems, and up till today, this hasn’t changed.

There are three main strategies for coping with challenges, being robust, being knowledgeable and flexible:

Robust Strategy: A robust strategy focuses on building resilience and designing systems that can withstand uncertainties and variations. In the SBPSC, this means developing a development plan and infrastructure that can adapt to different scenarios, considering the range of uncertainties such as reservoir characteristics, fluid properties, and operational challenges. By incorporating redundancy, flexibility, and contingency measures, a robust strategy aims to minimize the impact of uncertainties and ensure continuous production and operation.

Knowledgeable Strategy: A knowledgeable strategy emphasizes acquiring and utilizing knowledge to make informed decisions. In the SBPSC, this involves extensive data gathering, analysis, and continuous learning from previous experiences. By investing in research, exploration, and data integration, the operators can enhance their understanding of the reservoir behavior, fluid dynamics, and operational constraints. This knowledge helps in optimizing drilling techniques, reservoir management, and production strategies, leading to improved efficiency and performance.

Flexible Strategy: A flexible strategy focuses on adaptability and responsiveness to changing circumstances. In the SBPSC, where uncertainties are high, a flexible strategy involves designing systems and processes that can quickly adjust to unforeseen challenges. This includes considering alternative development scenarios, fluid management approaches, and recovery mechanisms. By maintaining a high degree of flexibility, operators can mitigate risks, exploit new opportunities, and optimize production even in the face of changing reservoir conditions or market dynamics.

Researchers Da Costa Fraga et al. (2015) concluded that overcoming the challenges of presalt exploration and production in the Brazilian Pre-Salt region was possible due to several factors. These factors include substantial investments in static and dynamic appraisal, the implementation of the WAG recovery strategy, intelligent well completion techniques, extensive use of technology, and collaborative efforts among multidisciplinary teams comprising geologists, geophysicists, petrophysicists, and reservoir engineers. Some examples of the well construction challenges that have been successfully addressed in the Pre-Salt cluster, as outlined by Pinheiro et al. (2015), are as follows:

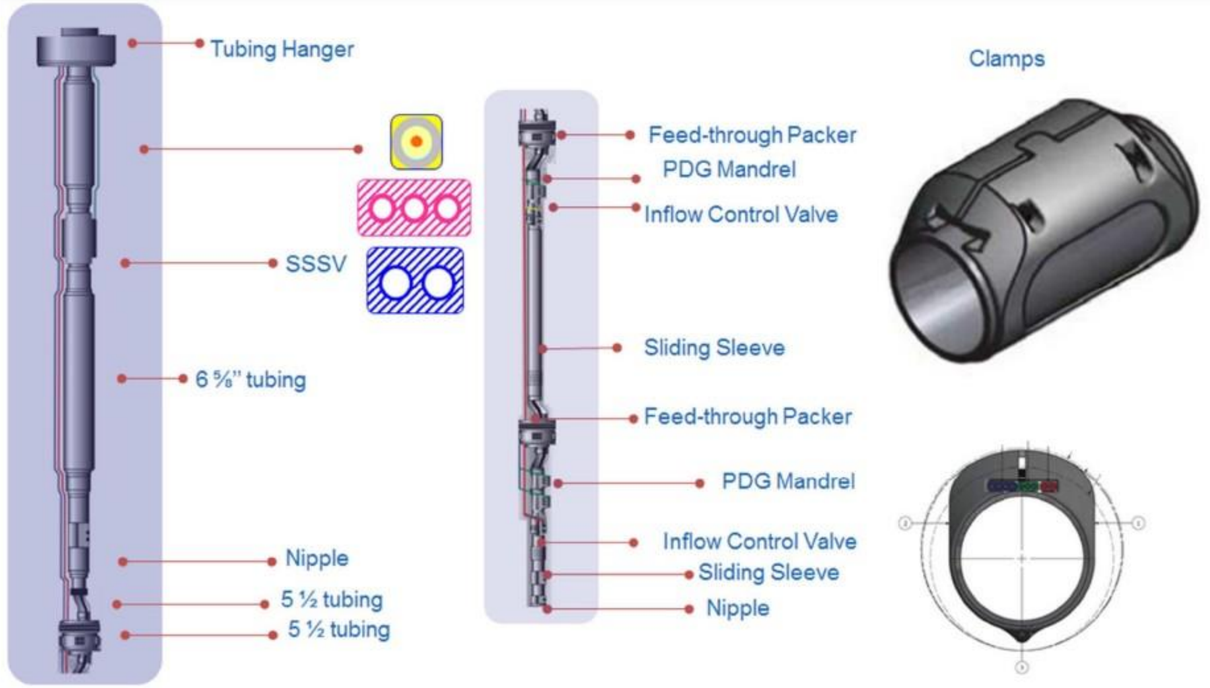
1. Drilling through extended sections of post-salt and salt layers with varying hardness using a riserless technique and a single bit trip.
2. Dealing with high formation temperatures, which affect salt mobility and impact drilling operations and casing resistance.

3. Optimizing casing design by simulating salt geomechanical loads and casing stresses using Finite Element Method (FEM).
4. Drilling through carbonate reservoirs with extensive salt sections exposed.
5. Optimizing bit and BHA (Bottom Hole Assembly) design to reduce costs while drilling through hard and thick carbonate sections.
6. Managing severe or total losses encountered while drilling through carbonate reservoirs with fractures and vugs by utilizing Managed Pressure Drilling (MPD) operations.
7. Selecting appropriate casing metallurgy for high carbon-dioxide and Hydrogen-sulfide reservoirs.
8. Addressing reservoir heterogeneity uncertainty through flexible completion design options (single vs. multi-zone completion).
9. Maximizing oil recovery by installing multiple-zone intelligent completions with remote-controlled valves, chemical injection systems, and pressure and temperature monitoring per interval. Additionally, optimizing well stimulation through multi-stage acid fracturing.

Initially, vertical well trajectories were chosen in the Pre-Salt development to mitigate geomechanical risks during salt drilling. However, theoretical and experimental studies were conducted to better understand salt behaviour and predict salt creeping, which allowed for casing and well optimization. In recent years, Petrobras has evaluated various well design and configuration alternatives, including sub-horizontal, multi-fractured, open hole, and single and multiple-zone intelligent completions. The implementation of intelligent completions in the Pre-Salt area began in 2012 with an injector well (9-RJS-665) in Lula Field, followed by a production well with a 7” casing configuration (Pinheiro et al. 2015).

Among the different well design options evaluated, the Large Bore Intelligent Completion has been the most widely used configuration, installed in over fifty percent of wells drilled in the past five years. This configuration involves a 9 5/8” super duplex casing cemented and perforated, along with a combined 5” and 5 ½” production string equipped with 4 ½” flow control valves for high flow rates (see figure 3). Acid stimulation is performed in each zone.

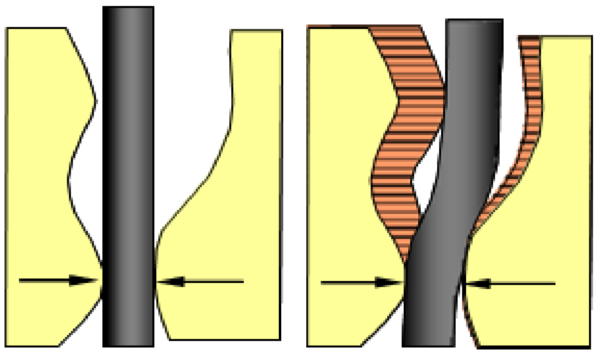
Figure 3: Large bore well completion schematic



Source: Pinheiro et al. (2015)

While this well design offers cost advantages, it has been implemented only when there is substantial reservoir knowledge to confirm the presence of a large vertically connected net pay single zone, which is a substantial and continuous zone of the reservoir that contains hydrocarbons (net pay) and is vertically connected.. The irregular shape or tortuosity of the borehole can significantly amplify the effects of nonuniform casing loading caused by salt movement. Proper cement placement opposite openhole zones is critical for successful well construction, particularly in salt sections, as inadequate cement fill can lead to casing bending and salt-induced borehole closure (See Figure 4).

Figure 4: Salt or cement holds casing at this point. Flow of salt causes bending of casing



Source: Beltrao et al. (2009)

Constructing deviated wells into thick salt layers presents another challenge. In such cases, the concerns about well integrity and casing collapse are especially significant. Remedial actions such as running a liner inside the casing opposite problematic formations and cementing the annulus between the two casing strings have been documented as effective measures to relieve and uniformize loading due to salt motion, preventing casing collapse and preserving well integrity.

The discovery of the first supergiant pre-salt field, Tupi, in 2006, presented significant drilling challenges, taking over 200 days to drill. However, thanks to advancements in technology and the knowledge gained from drilling over 250 wells in the area, the drilling time has been significantly reduced (Pinheiro et al., 2015). Since 2013, more than five wells of this type have been constructed, with the fastest one being drilled and completed in less than 92 days, setting a record for the Pre-Salt region. Consistently, completions can now be performed in less than thirty days.

The fastest well in the Pre-Salt Cluster was built in 2014 in the Lula Field, taking less than 100 days, achieving a reduction of over 20 days. This success can be attributed to various practices adopted by the project and intervention team during the execution phase, as well as the utilization of a dual intervention rig. In an effort to reduce costs associated with Pre-Salt wells, the well cost reduction program (PRC Poço) was established at the end of 2012. This program integrates all Exploration and Production areas and promotes a culture of continuous learning within Petrobras Pre-Salt project teams. Through testing different technologies and designs, continuous improvement for future projects and the progressive extension of technology have been achieved.

The success in reducing both time and costs of well construction can be attributed to the implementation of best practices throughout the project management process, from planning to execution. These practices have influenced well construction teams to apply value-creating solutions. It is crucial to maintain this continuous process during Pre-Salt Production development.

Despite the challenges faced, the campaign costs of Pre-Salt well construction in the Lula and Sapinhoa fields have been significantly reduced due to an accelerated experience curve and corporate initiatives. The experience gained since the first wildcat well and the extensive use of well data are key factors in maximizing performance and reliability for future Pre-Salt wells.

The contaminants in the produced fluids created the necessity of a careful definition of the materials to be used in flowlines and risers, well tubulars, and processing plants. The Petrobras Research Center launched a test of different alloys in order to select the most suitable materials.

Due to the challenges of well drilling in the presalt region as depicted in Figure 2, integrated planning and integrated teams were adopted for well construction, this has helped with standardization and cost reduction, and has accelerated the gaining of experience for young professionals. 5th and 6th generation rigs were utilised, rig automation, and a learning curve approach utilised.

The following are some of the solutions to the challenges:

1. For flow assurance, there was the identification of its critical aspects through lab experiments, mitigation measures were taken as adequate thermal insulation of risers and pipelines, flexibility in plaforms to displace oil content in flowlines by diesel during shutdowns and implementation of downhole chemical injection systems.

2. The Brazilian presalt has been the first to implement many technological feats around the world such as the buoy supporting risers, deepest flexible risers, deepest offshore well etc as mentioned by (Da Costa Fraga et al., 2015).

3. The phased development plan for the SBPSC (Santos Basin Pre-Salt Cluster) is a strategic approach chosen due to the large scale of the project and the uncertainties involved. This approach is based on Petrobras' experience in developing deepwater fields in the Post-Salt region. The phased development strategy offers several advantages, including better financial balance by aligning expenditures with revenues and allowing time for learning from the initial field results. As more data is gathered, particularly dynamic data, the flow model becomes more reliable, enhancing its predictability. Consequently, it is anticipated that the uncertainties and risks associated with the final development systems will be reduced.

4. Reservoir characterization plays a significant role in addressing the challenges, implementing solutions, and achieving superior performance in pre-salt exploration wells in Brazil. In the context of the Brazilian pre-salt, reservoir characterization involves understanding the complex geological and petrophysical properties of the pre-salt reservoirs.

The reservoir characterization process helps in identifying the external geometry, internal barriers, and facies variations within the reservoir. This information is crucial for determining reservoir connectivity and defining the drainage plan, which is essential for optimizing production and recovery.

Additionally, reservoir characterization helps in modeling rock types and their association with petrophysical properties. This understanding aids in estimating static and dynamic properties such as porosity, permeability, relative permeability, and capillary pressures. These properties directly influence the flow of fluids within the reservoir and impact production performance.

Reservoir characterization also addresses the challenges posed by heterogeneity, fractures, and the interaction of reservoir rock with injected fluids. By accurately characterizing these aspects, engineers can develop effective strategies for reservoir management, well construction, and production systems design.

Ultimately, reservoir characterization provides critical insights into the behavior and potential of the pre-salt reservoirs. It guides decision-making processes, enables the identification of optimal recovery mechanisms, and contributes to the overall goal of boosting superior performance in pre-salt exploration wells in Brazil.

There has been major advances in seismic imaging from the 1960's up to the 1990's in the Campos Basin as outlined by (Bruhn et al., 2017). However, this advances were not shared with the Santos Basin particularly because the seismic data available for the Santos Basin was only 2D seismic which is rather ineffective, progress to improve the 2D seismic data sets began from early 2000's and this lead to a large 3D seismic campaign for exploratory purposes (Bruhn et al., 2017).

2.4 Drilling Time Reduction

Efficient drilling operations play a crucial role in the success and economic viability of oil and gas exploration projects. As drilling activities become more complex and costly, the industry continually seeks innovative methods to reduce drilling time while maintaining safety and efficiency. This subchapter focuses on exploring the various approaches, technologies, and strategies employed to minimize drilling time in the oil and gas sector. By understanding the key factors influencing drilling time and examining successful case studies and best practices, we can uncover valuable insights that contribute to improved operational performance, cost savings, and overall project success.

There have been several technological enhancements and innovations to improve drilling performances such as automation propelled by 3D visualisation tools, "at bit" geo-steering, intelligent push-the-bit Rotary Steerable System (RSS) by Haliburton, and directional drilling bit guidance system to mention a few (Teodoriu & Bello, 2021). One of the well-known drilling enhancement and drilling time reduction technologies is the Straight-hole Drilling Device along and the Lean Profile. The Lean Profile is an innovative technique of casing program that leads to a slimmer well profile, it provides a dramatic reduction in drilling time and cost (Calderoni et al., 1999; Ferrari et al., 2000). Calderoni et al. (1999) summarised field experiences and results where up to -40% time was achieved using the Lean Profile technique.

Utilising the appropriate technology helps in drilling time reduction by a significant percentage and/or days. For example, in the case study of Galarraga et al. (2016), they recorded 12 days drilling time reduction when they implemented the new fixed cutter structure layout that was used to drill through hard, abrasive conglomerates in deep wells. Saboori et al. (2018) mentioned that the optimum selection of drilling fluid is a key factor in minimising drilling time and cost. Sometimes synthetic-based muds (SBMs) are utilised, and they can reduce a well drilling time by 35–55% which will in turn reduce the cost of the well (Onuh et al., 2020). Gao, (2020) stated that with glycol mud, the average drilling time was reduced by 10 days, wellbore washout was less than 6%, and very low formation damage was observed.

In order to achieve rapid drilling in deep and hard formations, the concept of particle impact drilling was put forward and the results proved that particle impact drilling technology can save drilling cost and drilling time, and increase drilling speed by about 2 to 4 times Fang et al. (2022). In the exploratory campaign of a pre-salt field called Buzios, Aguiar et al. (2019) offered a technical solution to the challenges of pre-salt drilling, the service provider applied an innovative approach based on two pillars: a model-based design approach, leading to two drill bit designs with improved cutting structure resistance, with dynamic stability, delivering the entire section in one bit run with higher ROP. The operator's objective in the exploratory campaign to develop the Búzios field in the Santos basin offshore Brazil, was to minimise drilling costs through elimination of unplanned trips. Accordingly, application-specific bit designs needed to be developed to optimise drilling efficiency in this section, aiming to drill the entire reservoir section in one bit run.

The downsizing strategy, reducing the number of casing sizes is also another form of drilling time reduction. In Muñoz et al. (2016), two wells were drilled applying the downsizing strategy and optimization of the process. The impact of the anticipated challenges in both holes was decreased because the design implemented preventive plans. Optimization of well-trajectory, probabilistic analysis (time and cost estimation) and introduction of new technologies and revision of standard procedures and practices are actions taken to reduce drilling time. This optimization reduced the drilling time by up to 27%. Reducing the number of casings is adopted as a well design optimisation strategy, with successful operations carried out on exploratory wells that only required three casings to be set. Key aspects of the well design optimization included drilling an extended second section without a riser and returning to the open sea, as well as drilling a longer final section to Total Depth (TD). The adoption of drilling exploratory wells with fewer sections, even in ultra-deepwater, has reduced drilling time to less than half the typical time it used to take to reach TD (Cunha, 2004).

Aleksandrov et al. (2015) in their drilling with-with-casing technology pilot test concluded that there can be a reduction of drilling time of up to 1.5 to 2.0 times if the non-retrievable drilling-with-casing-technology drilling method is implemented where top hole sections are covered by permafrost rocks. Foidaş et al. (2019) stated that one of the advantages of the casing while drilling (CwD) is total drilling time reduction by eliminating the time and effort implied by tripping the casing string. Therefore, after reaching the depth for setting the casing, the drilling fluid is replaced by cement, and the float collar is installed before the drilling begins. Therefore, the operations performed before conventional casing and cementing are avoided.

The economic downturn of the oil industry is to seek an innovative solution for reducing the cost of wells while improving performance, the main drivers to reduce this cost involve a reduction of materials, services and equipment. Knowledge and expertise also help in drilling wells in minimum time as demonstrated by Guzmán et al. (2006), stating that drilling time was able to be reduced over 5 years without affecting personnel safety and environmental issues. Calderoni et al. (1999) mentioned that drilling time and the daily fixed cost affect the economic impact the most. Major cost savings are a result of drilling time reduction and its reduction in exploration can be achieved through drilling system design and operations which are technology dependent or through optimising the procedures and methodology of the exploration campaign, and its team approach. Ferrari et al. (2000) stated that drilling time reduction does not only depend on technology and it is not only important for the sake of time saving and profit increase but also less impact on Health Safety and Environment (HSE). It offers advantages in terms of material consumption and waste production. Drilling time reduction is a challenging and crucial task for many operators and service providers (Kretsul et al., 2015), however, through the use of the appropriate technology and approach, drilling time can be reduced significantly, for example, Kretsul et al. (2015) describes how a multidiscipline team of drilling contractors and service providers have significantly reduced drilling time in the Valanginian horizontal wells in Siberia through the adoption of new technology and employing the Engineered

Drilling System (EDS) approach.

According to Aguiar et al. (2019), drilling activity in Brazil has been primarily focused on finding economically viable ways to develop the pre-salt reserves after a major oil discovery was made in the pre-salt province. The Brazilian National Petroleum Agency (ANP) has stated that exploratory activity in Brazil reached an all-time low in 2018, as there had been a halt in bidding rounds from 2008 to 2017, which was broken by an exceptional round in 2013. The exploratory campaign outlined in this paper represents part of the resurgence of exploration activity in Brazil. Operators were challenged to mature projects for development, while service providers were under financial pressure due to a challenging market environment.

To reduce drilling time, the drilling process must be optimised and this optimization not only improves the process but also improves the logistics, and remote control rooms, and expedites timely decisions, which also results in the drilling time reduction. The knowledge acquired during previous drilling (learning curve) and completion projects helps to reduce drilling time. According to Fernandes et al. (2020), the contracting strategy can also play a significant role in cost reduction and time savings, Passos et al. (2012) suggest an outsourcing strategy based on integrated project management to reduce the number of contractors and to overcome many of the drilling challenges.

Performance reports from some of the wells in the Gulf of Mexico had an estimated 60 hour large hole drilling time reduction due to improved Rate of Penetration (ROP). The Bighorn 8-35 is the eighth ultra-deep well drilled in the Wyoming Madden Deep Unit (MDU) of the Wind River Basin, to drill this well, Burlington redesigned the casing/bit size program for the Bighorn wells to significantly reduce time and overall cost. The first well drilled in the Wyoming Madden Deep Unit, the Bighorn 5-6 resulted in a drilling time reduction of 34% saving costs of up to $10 million (Chandler et al., 2003). Earlier research has revealed that only a minor fraction of the total drilling duration involves the physical cutting of rocks in the wellbore by the drill bit. The majority of this time is consumed by downtime components, such as moving the drill rods in and out of the well. One approach to enhance the drilling operation is to enhance the bit’s effectiveness and decrease the downtime associated with drilling. This can be achieved by optimizing the weight on bit (WOB) and rotational speed for a particular bit and rock formation, resulting in an increase in drilling rate. Additionally, increasing the ratio of drilling time to bit trip time can also improve drilling efficiency (Cheraghi & Peyman, 2013). The prediction of the drilling ROP is one of the key aspects of drilling optimization due to its significant role in reducing expensive drilling costs. Minimising the drilling cost can be achieved by optimising the controllable drilling parameters such as WOB, revolutions per minute, and flow rate (FR) on the ROP (Bani et al., 2021).

Barakat et al. (2021) aimed to integrate Risk Management (RM) techniques with the philosophy of Non-Productive Time (NPT), along with other concepts such as Systems Thinking, Synergy, Continuous Improvement, and Total Quality. They developed a Java software model that represented NPT as an undesired event with a probability of occurrence, using RM terminology. They also proposed a set of risk control recommendations to reduce NPT and improve rig performance. By integrating the concept of NPT with the science of RM, the researchers introduced a novel approach to minimising drilling losses.

Overcoming operational difficulties makes us learn the best way to drill the exploration wells and even the subsequent development wells, build guidelines and procedures and implement high standards of safety and reliability. At the same time improving the drilling performance and consequently, reducing the overall cost. Alves et al. (2009) presented the highlights of Petrobras E&P program to make the best use of these opportunities to leverage the well-construction learning curve. Drilling into the subsalt reservoir is a highly challenging task due to several factors. The wells are extremely deep, ranging from 5,500 to 6,500 metres, and the water depth is also very high, typically between 2,100 to 2,500 metres. During the exploratory phase of drilling programs, well design has traditionally been an iterative process, with past drilling experiences informing and guiding future design improvements. The efficiency of drilling in a given area usually improves significantly at first, but eventually reaches a point of diminishing returns. This performance progression is commonly referred to as the ”drilling learning curve.” However, rather than relying solely on trial and error to improve drilling design, it is possible to accelerate the learning curve by focusing on fundamental principles and applying them consistently. This can result in significant cost reductions and improved performance. According to Flores et al. (2011), the drilling campaign in block C-M-592 in the Campos basin has witnessed a significant reduction in drilling times, exceeding 30%, as a result of implementing appropriate new technologies and standardised, fit-for-purpose practices. The success can be attributed to various measures, including mitigating shocks and vibrations, employing slender casing designs, utilising the latest generation of drilling bits, and establishing a clear process for capturing best practices and lessons learned. In this article, the approach adopted by operators and drilling contractors to reduce drilling time begins with the partnership and collaboration between the parties (drilling contractor, operator and well drilling service provider) and then the created four-step model for carrying out change, the Drilling Rig Package, Integrated Services Package and Directly Procured

Services DID-PDCA methodology. The following paragraphs describe how four Best In Class (BIC) wells were yielded and how the GdM4 well drilled in 2020 became the fastest pre-salt well ever drilled with its 18 dry-hole days mark.

In an offshore oil and gas campaign, the operator is the company that is responsible for managing the overall project and the contractor is hired by the operator to perform the drilling task while the service provider provides specialised equipment or services needed for the operations. All three parties work together to ensure the success of the exploration, with the operator managing the overall strategy and the contractor and service provider executing specific tasks. The relationship between these parties is often governed by contractual agreements that outline these respective roles and responsibilities.

3 DRILLING METHODOLOGY

In the pursuit of efficient and successful drilling operations, the development of effective drilling methodologies is paramount. Building upon the achievements and lessons learned from the drilling time reduction efforts, this subchapter delves into the drilling methodology employed during the exploration campaign in order to achieve outstanding results. By examining the specific techniques, processes, and best practices utilized, we aim to provide a comprehensive understanding of the methodology that contributed to the successful drilling of four best-in-class wells. This subchapter serves as a valuable resource for professionals in the field, offering insights into the strategic planning, operational execution, and technological advancements that led to significant reductions in drilling time. Through a detailed analysis of the drilling methodology, we aim to uncover the key factors and approaches that can drive efficiency, optimize performance, and pave the way for future drilling excellence in similar exploration campaigns.

The definition of partnership is quite extensive and can vary depending on the context. One perspective on partnership, as presented by Yeung, Chan, & Chan (2007), is through the concept of ”project alliancing.” This approach emphasises the importance of formal contracts, gain-share/pain-share agreements, trust, long-term commitment, a win-win philosophy, cooperation, communication, and adequate resources with top management support. (Robson, 2004) highlights the potential benefits of partnering over the traditional approach of daily rates for rentals and discretionary services, citing a 20 percent improvement in performance based on a review of 39 out of 56 papers published by the Society of Petroleum Engineers between 1990 and 2004. Operators may have various reasons for pursuing such partnerships, including expertise, cost reduction, and risk-sharing.

The drilling methodology used is DID-PDCA. PDCA is a popular methodology used for process improvement and problem-solving, it was initially developed for quality management but has since evolved to become a powerful tool for understanding the administrative process and problem-solving in various business environments including oil and gas Midor et al. (2022). The PDCA cycle is an iterative method that can be used for deploying new ideas and for solving problems, and it can be deployed at all levels of an organisation, from the board to the operation floor. The drilling rig package refers to a comprehensive set of equipment and systems necessary for drilling operations. It includes the actual drilling rig, which is a large structure used to drill wells, as well as various components and auxiliary systems that support the drilling process. The drilling rig package typically includes items such as the drill string, drilling mud systems, well control equipment, and other tools and machinery required for drilling operations. The integrated services package refers to a combination of different services and solutions provided by a company or contractor in the oil and gas industry. It involves the integration of multiple aspects of the drilling operation to streamline the process and improve efficiency. This can include services such as drilling, well construction, well testing, completion, and production optimization. By integrating these services, companies aim to optimise performance, reduce costs, and enhance overall project execution. Directly procured services are services that are obtained directly from external vendors or contractors by an operating company. In the context of drilling operations, these services are typically specialised services or expertise that are not available in-house or require specific technical knowledge. Examples of directly procured services in the drilling industry could include well logging and evaluation, cementing, directional drilling, wireline services, and well stimulation services. The operating company contracts these services directly with external service providers to fulfil specific needs during the drilling process. The Drilling rig package, Integrated service package and Directly procured services together form the DID shared ownership and it follows the methodology known as the ”Plan-Do-Check-Act” (PDCA) or ”continuous improvement cycle”, hence the term DID-PDCA. This approach as implemented in the campaign involves the steps in Table 1.

The cyclical nature of the steps involved in achieving sustained improvements in drilling efficiency requires ongoing attention and effort from all parties involved. Therefore, it is essential to use a methodology that incorporates all aspects of drilling management into daily organisational practices. The PDCA methodology is a proven method for achieving continuous improvement. The DID-PDCA methodology, as illustrated in Fig. 5, is a modification of the PDCA methodology used specifically for successful partnerships between drilling rig operators and vendors. The DID-PDCA methodology involves several steps, starting with a tender strategy to align the interests of all parties involved before contract signature. Workshops are then held before the first well to allow leaders and engineers from service providers and operators to get to know each other, map risks

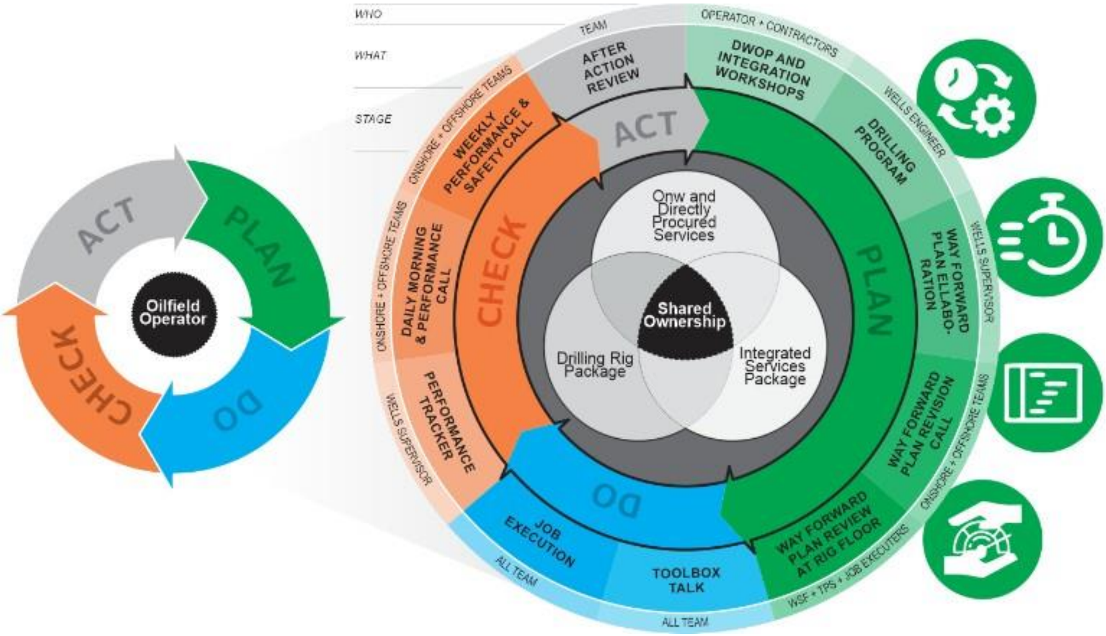
Table 1: Implemented DID-PDCA integrated approach

Phase	Activities
Plan	- DWOP and integration workshops and analysis to determine key criteria and parameters for improving drilling efficiency, setting goals and tasks, and developing a plan of activities. - Drilling program - Way forward plan elaboration - Way forward plan revision call - Way forward plan review at the rig floor
Do	- Toolbox talk - Job execution
Check	- Performance tracker - Daily morning performance call - Weekly performance and safety call
Act	- After action review and continuously taking measures to enhance the efficiency of activities in the drilling process

and opportunities, and facilitate communication. Delivery the Well On Paper (DWOP) workshops are held before each well, involving engineers, toolpushers, and wells supervisors to lay out opportunities and incorporate lessons learned into procedures. These workshops also provide a forum for discussing pain points and gaining insights into equipment use. After mapping the opportunities from the workshops, the Drilling Program is completed and approved by both Operator and Well drilling service provider before being provided to the rig crew. The crew then implements the program during the drilling operation, and data is collected and analysed to identify areas for improvement. Based on the analysis, changes are made to the program, and the process starts over again. Using the DID-PDCA methodology allows for continuous improvement throughout the drilling campaign, leading to improved efficiency, reduced costs, and increased productivity. The methodology serves as a framework for future studies in the drilling industry, as it highlights the importance of collaboration, communication, and continuous improvement in achieving success.

The Wells Supervisor elaborated a Way Forward Plan (WFP) based on the drilling program before each operation piece, which was reviewed and refined by all parties through calls and presentations to the crew. Performance tracking involved daily and weekly meetings to discuss data collected by the wells supervisor, which were used to improve procedures and equipment upgrades, with a focus on delivering goal zero (no harm, no leaks). After action reviews were held to identify areas of improvement and capture points for future operations. The leadership played a crucial role in keeping the team's energy high, and a list of opportunities was created for the four wells to be drilled.

Figure 5: DID-PDCA cycle adopted by companies for the campaign



Source: (Own work)

To track and improve performance during drilling operations, the DID-PDCA cycle illustrated in figure 5 was initiated, involving all parties and four distinct tracking moments: daily tracking by the Wells Supervisor with assistance from the Real-Time Operations Center (RTOC), weekly Performance and Safety calls, and After Action Reviews (AAR). The Wells Supervisor compiled data on performance versus the plan and presented it during daily calls, triggering discussions on improvements. Topics of longer analysis were discussed in weekly meetings, led by the Operator Wells Operations Manager and Rig Superintendent. An action tracker was used to follow up on initiatives. The AAR was a final review to capture improvement opportunities and record them for future operations. The team's energy was crucial for success, and a list of opportunities was created for improvement.

Throughout the drilling campaign, the team identified several opportunities for drilling time reduction. Some of these were selected for further investigation, which often questioned conventional practices and presented implementation challenges. The actions pursued to improve drilling efficiency were categorized into four groups: Project Optimization, Speed Improvement, Reduction in Flat Times, and NPT mitigation. Overall, these actions contribute to the efficient and effective drilling of wells, reducing costs and improving performance.

Under the Project Optimization category, the team implemented a slender hole concept with 4 phases for drilling pre-salt wells, instead of the traditional 5 stages. This design utilized 3 casing strings instead of 4, reducing the total drilling time by approximately 17 days and significantly optimising the total cost. Regarding Speed Improvement, the team optimised the utilisation of dual-activity, ensuring the perfect timing of auxiliary floor activity to feed the materials and resources to the main floor adequately. The team also made improvements to the ROP and connection time, with slip-to-slip targets set to 5.5 minutes and bottom-to-bottom at 13 minutes. The connection time improvement initiatives also encompassed the Riser Running/Retrieving time optimization, with a target running speed of 116 metres/hour. Although this target was not met, the implementation of better routines enabled a 30% improvement, reaching an average of 80 metres/hour.

Additionally, the team implemented soft speed and auto-drill systems to mitigate torsional vibration and reduce stick/slip oscillations during drilling operations, see Table 2. The use of these systems was optimised during the well's construction through collaborative work between all parties involved in the drilling operations. The data from soft speed and auto drill were reviewed, and adjustments were made during drilling, resulting in a considerable increase in the ROP.

To ensure standard practices and minimise connection time, Operator, Drilling Contractor, and Services Integrator jointly designed a procedure defining roles and responsibilities during the connections. This procedure allowed tracking of well conditions, and any deviation from these practices was shared to improve future operations. The team reviewed the connection times daily, with deviations investigated and mitigated. Practices included details on surveying, back-reaming, and connection times.

Various strategies were employed to reduce flat times and NPT during a drilling campaign. The strategies include reducing pressure tests during riser operations, optimising pit management plans, managing deck space, utilising Active Heavy Compensation (AHC) cranes, implementing simplified beacon arrays, using special autofill float valves in Bottom Hole Assemblies (BHA)s, and using Dual Gradient Drilling with Mud Cap Drilling (DGMCD) instead of Managed Pressure Drilling (MPD). Additionally, there was an all-around approach towards BOP reliability and the implementation of an asset integrity program to maximise equipment availability and minimise downtime. The partnership was between the operator, drilling contractor and well drilling service provider and it began in the tender strategy with the leadership of the operator. The goal is to align as much as possible with the interests of the different parties. After the contract signature, a series of documents and engagements were utilised to maintain the alignment of these interests and improve on them. Leaders' and engineers' workshops were held for acquaintance and the mapping of risks and opportunities of the operations to be carried out. Delivery Well On Paper (DWOP) was carried out with all parties and workers involved, from the second well the procedures were improved using the lessons learned.

Operators might achieve a performance improvement of 20% using partnering compared to the traditional approach of daily rates for rentals and discretionary services (Robson, 2004). Such partnering might be motivated by several factors on the lenses of operators, being its expertise, cost reduction or risk-sharing the most common. On a more conventional operation to drill a well, the operator engages in signing circa 60 contracts covering a series of needs ranging from the drilling rig and logistical support to downhole services. The premise of ”one-down, all-down,” was adopted for the services on the drillship, i.e., any of these services affect the financial outcome of the whole package, aligning the interest of all parties on keeping uptime as high as possible.

Well drilling service provider integrated several well engineering and drilling services and the contract was structured on an outcome basis with incentives to make the most use of the expected uptime of the rig package. Some logistical services such as helicopters and road transportation were hired directly. This approach reduced the high number of contracts to nine with three companies. To help the drilling contractor deliver the best possible service and to avoid down manning and loss of experience, the operator funded the rig’s crew for the months between the signing of the contract and the commencement of the operations.

A loss of experienced workers in the company is detrimental because it gives it a characteristic of a new company, hence, old challenges could become new challenges to new workers, this can pose a significant challenge as stated by Flores et al. (2011) that an aggressive exploratory campaign to drill wells within a short time poses a significant challenge for a newly created operating company. Therefore it was essential to keep the experience alive for delivering quality services. Putting more focus on delivering quality services rather than a prescriptive list of technical specifications, flexibility in the terms of the contract to help include minor requirements that could improve the safety and quality of the work’s performance, and it was possible to incorporate lessons learned and features to the drilling package, ensuring that the services delivered were of the highest quality.

The identification of performance improvement actions was a constant during the drilling campaign. Some of these opportunities would be identified and selected for further investigation, not infrequently questioning conventional practices and raising challenges for their implementation.

Within the realm of the drilling methodology, various subtopics played a crucial role in achieving the remarkable outcomes of the exploration campaign. Each subtopic represents a specific area of focus aimed at optimizing design, enhancing speed, reducing fixed times, mitigating Non-Productive Time (NPT), reinforcing safety culture, and implementing efficient processes. In this section, we delve into these subtopics, providing insights into their significance and contribution to the overall success of the drilling operations. By examining the design optimization strategies, speed improvement techniques, fixed time reduction approaches, NPT mitigation measures, safety culture reinforcement initiatives, and meticulous preparation efforts, we gain a comprehensive understanding of the comprehensive framework that underpins the drilling methodology. Through this exploration, we uncover the valuable insights and practical strategies that were instrumental in achieving operational excellence, ensuring safety, and driving performance throughout the exploration campaign.

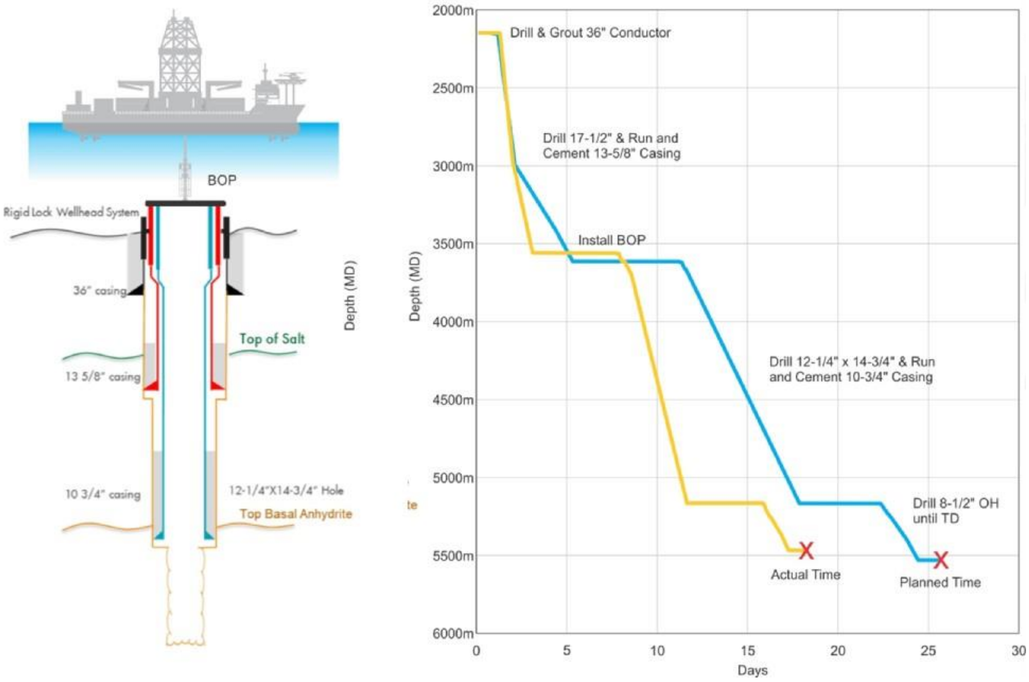
3.1 Design optimization: Slender well

The design optimization of a slender well concept for pre-salt wells was a key area of focus for the drilling team. The traditional approach involved drilling the well in five stages, but the team set a goal to utilize a 4-phase concept that would reduce the total drilling time and optimize costs.

Under this new concept, the well progressed past the 36” conductor directly with the 13-5/8” casing, skipping the traditional 20” (See Figure 6). The salt section was then drilled with a 12-1/4” bit, which was increased to 14-3/4”, and lined with a 10-3/4” casing. Finally, the reservoir was drilled with an 8.5” drill bit and left open for open-hole completions. The well was equipped with only three insulating casing strings, instead of the traditional four.

This optimization resulted in a significant reduction in the total drilling time, cutting around 17 days from the process. It also contributed to a significant cost reduction, as fewer casing strings were needed, which meant fewer materials, equipment, and personnel. The slender well concept allowed the drilling team to achieve their goal of improving drilling efficiency and performance, reducing costs and increasing overall project success.

Figure 6: Time versus Depth curve for well GdM4 from Spud-in to TD. The total time spent in the well was longer, however core, profiling and abandonment activities were excluded.



Source: (Own work)

3.2 Coaches - Point of reference of the A&A Program

Coaches are essential to the success of the Assist and Assure (A&A) Program, possessing strong coaching skills and expertise in drilling and HSE. Trained to deploy, monitor crews, and provide feedback, they play a pivotal role. On-site, these coaches ensure every team has an A&A program reference, facilitating meetings, ensuring task readiness, and evaluating controls. Beyond this, they reinforce on-board safety culture, consistently assess behavior, and guide improvements for optimal team performance. Their collective expertise is integral to the program's success, offering essential support and fostering a safer working environment.

3.3 Speed Improvement

Dual activity utilization optimization: Advance planning as well as a synchronized process ensured perfect timing of auxiliary drilling floor activity to properly feed materials and resources to the main floor. Gaps between activities have been eliminated. Below are some examples of simultaneous activities carried out on both drilling floors:

1. Completing the environmental conditions assessment while preparing the well for

the spud and descending the 36” casing on the auxiliary floor.

2. Preparing and lowering the 13-5/8” casing (including the 5” drillpipe stinger string) and the High Pressure Wellhead Housing to the mudline on the auxiliary floor while drilling the riserless section 17-1/2” on the Main table. When drilling is complete and the bit hits the seabed, the drillship is moved to align the auxiliary floor to the center of the wellbore and the casing is driven into the wellbore.

3. Preparing and lowering the BOP and drill riser on the main floor during the 13-5/8” casing grouting job.

4. Preparing and testing the cement section (cement heads, operating valves, safety valves, pupjoints and hoses) on the auxiliary floor during casing operation, eliminating chances of NPT due to unexpected leaks. The section is then retested during circulation for cementation, which is carried out on the auxiliary floor.

5. Assembling and laying the 10-3/4” production casing while drilling the 12-1/4” x 14-3/4” section.

6. Handling all drilling BHAs offline: breaking 17-1/2” BHA and mounting 12-1/4” BHA while descending BOP and drilling riser; mounting 8-1/2” BHA while drilling 12-1/4 section; mounting the 8-1/2” core BHA while drilling the 8-1/2” section.

7. For core operations, a full risk assessment was carried out by all parties involved, followed by different simulations on the platform site. Upon completion of drilling, the complete drill set was transferred to the auxiliary floor and placed together (internal barrel still containing the cores) and the cutting work was done on the pipe deck, eliminating the time spent handling the barrel rotary table.

ROP (Penetration Rate) increase: The rig was equipped with essential systems that allowed its use to the limit: Soft Speed and Auto-drill of which its parameters from the test performed during the drilling can be seen in table 2. The former uses automated vibration dampening to mitigate torsional vibration and reduce slip/stick oscillations during drilling operations. The second smoothly controls the distribution of the drill line through the drill winch’s brake lever, using precise stepper motor technology and multi-parameter control, ensuring constant bit contact with the bottom of the hole.

The use of these systems was optimized during the construction of the wells due to the collaborative work between all parties involved in the drilling operations. Basically, after drilling the first pre-salt well of the campaign, all Soft Speed and Auto-drill data were taken from the platform database and sent to be reviewed by the system manufacturer and Operator specialists. Afterwards, many meetings took place to bring all the parties involved together to share learnings and define a plan for the next drillings. In addition, some tests and adjustments were made during drilling with the participation of all parties involved. This very collaborative work and the application of the PDCA process enabled a considerable increase in ROP.

Connection time improvement: The operator, drilling contractor and service integrator have developed a joint procedure to define roles and responsibilities during connections. The objective was to minimize connection time (bottom to bottom) while ensuring that the well was properly cleaned and remained in pristine condition. Standard connection practices were proposed to allow tracking of well conditions, and any deviations from these practices were to be shared to improve future operations. An example of the connection time monitoring can be seen in Figure 7. Practices included details on inspections, back-reaming and connection times. Time targets for slip to slip were set to 5.5 minutes, botton to bottom time was set at 13 minutes and times were reviewed daily during drilling with deviations investigated and mitigated. Connection time improvement initiatives also encompassed the optimization of riser decision and removal times. The riser maneuvering speed was targeted at 116 meters / hour, which although it was not reached, the implementation of better routines allowed a 30% improvement, reaching an average of 80 meters / hour. Figure 7 illustrates an example of connection monitoring during the 8-1/2” section of one of the wells, showing outliers and targets.

Figure 7: Example of connection time monitoring provided by the Remote Operations Monitoring Center (RTOC).

Source: (Own work)

Table 2: Parameters from Auto-drill and Softspeed tests performed during the drilling of the 12-1/4” x 13-3/4” phase of a Saturno well.

Start time	start depth (m)	Mode	Period (s)	Pre Factor 1 (%)	Pre Factor 2 (%)	Active mode	WOB set-point (klb)	ROP Max (m/h)	ROP set-point (m/h)	WOB Max (klb)	Filter Constant	Hook load Filter	Resp. Time (s)	ROP Range (m/h)	WOB Range (klb)
09:00	4029	Auto	6.6	28.3	43.3	WOB	45	40			5	0	2	m/h	30-40
10:30	3980	Auto	6.6	28.3	43.3	WOB	30	50			5	0	5	20-25	25-35
12:20	4070	Auto	6.6	28.3	43.3	WOB	35	50			5	0	5	21-24	28-40
12:30	4074	Auto	6.6	28.3	43.3	WOB	35	50			5	0	6.5	15-20	30-35
13:04	4084	Auto	6.6	28.3	43.3	WOB	40	50			5	0	6.5	20-24	35-45
13:26	4089	Auto	6.6	28.3	43.3	WOB	40-45	50-55			5	0	3	25-30	40
13:50	4110	Auto	6.6	28.3	43.3	WOB	45	60			5	0	2	35-38	40-50
14:50	4131	Auto	6.6	28.3	43.3	ROP			25-30-35-40	55	5	0	2	25-30	20-40
15:53	4163	Auto	6.6	28.3	43.3	ROP			35-40-45	50	5	0	2	35-40	45-50
16:25	4174	Auto	6.6	28.3	43.3	ROP			30-35-40-45	50	5	5	2	35-45	40-50
17:45	4213	Auto	6.6	28.3	43.3	ROP			30-35-40-45	50	5	5	2	30-35	45-50
18:20	4235	Auto	6.6	28.3	43.3	WOB	40	60			5	5	2	30-35	45-50

3.4 Fixed Time Reduction

Riser pressure test optimization: During the drilling riser descent, the string is generally tested every 500m to mitigate the potential need to remove the BOP. Historical data on pressure test results during riser descent was analyzed to assess its actual applicability and probability of failure. The analysis of historical data demonstrated the low probability of failure during these operations. As the consequence is financial - lost time while the well is safe - the operator and the drilling company shared the risk of reducing these tests to the point that, at the end of the manoeuvre, the BOP is tested only once after locking in the head of the pit. The reduction in the number of tests during riser operations saved up to 14 hours per BOP maneuver. During the campaign, not a single test revealed any flaws.

Tank management plan: To reduce the fixed time involved in fluid changes during drilling operations, a tank management plan was implemented. This plan involved using the vessel’s ability to store and transfer different types of fluids simultaneously, which helped in minimizing the time required for cleaning and aligning tanks during fluid changes.

The tank management plan was designed to optimize the use of the available tanks and minimize the downtime associated with fluid changes. This was achieved by carefully planning the sequence of fluid changes and ensuring that the tanks were cleaned and aligned in advance. The plan also included the use of specialized equipment and personnel to ensure that the tank cleaning and alignment processes were carried out efficiently.

The implementation of the tank management plan resulted in a significant reduction in the fixed time associated with fluid changes during drilling operations. This allowed the drilling team to focus on the critical wellpath and reduce the overall drilling time, resulting in significant cost savings for the project. Moreover, the tank management plan ensured that the drilling operations were carried out smoothly and efficiently, minimizing the risk of delays and downtime.

Deck space management: Deck space management is a critical aspect of drilling operations as it directly impacts the efficiency of the entire drilling process. Poorly planned or inefficient distribution of tools and equipment can result in increased fixed times and lost time due to unnecessary movements. Therefore, it is essential to have an effective deck space management plan that optimizes the use of available space, reduces exposure to risk, and maximizes the efficiency of the drilling operations.

In this case, both companies involved in the drilling operations worked together to create an optimal deck space management plan. This plan involved several workshops where representatives from both companies discussed and evaluated the best way to distribute the equipment and tools on the vessel. This process allowed the teams to identify any potential bottlenecks and address them before the drilling operations began.

The outcome of this process was a comprehensive ”distribution map” that was communicated to all teams involved in the drilling operations. This map provided clear guidelines on the location of each piece of equipment, allowing the teams to easily access them and minimize unnecessary movements. As a result, the use of the crane was minimized, reducing the exposure to risk, and the efficiency of the drilling operations was maximized, reducing fixed times and increasing overall productivity.

Effective deck space management is crucial for optimizing the efficiency of drilling operations. The collaborative approach taken by the two companies in this case allowed for the creation of an optimal distribution map, minimizing the use of the crane, reducing exposure to risk, and maximizing the efficiency of the drilling process.

Use of AHC Crane: Some vessels are equipped with Active Drive Compensated Cranes (AHC), which allow the installation of subsea equipment without drilling motion compensators. With this equipment available, the first locking of a THS (Tubing Head Spool) was performed during well ON-11. The THS operating operation was entirely carried out in parallel with the drilling floor activity, and the tool was locked at a depth of 1640 m. It allowed for at least 2 hours of reduction in the well’s critical path, along with the benefit of freeing up the auxiliary drilling floor for further column preparation. Correlation wells where such an operation was performed on the auxiliary drilling floor indicate that the total time for moonpool preparation, running operation, release of the main well center, locking and testing and retrieving the column would take up to 3.5 days versus a total operating time of 2.0 hours with the AHC Crane. In addition, it contributes to less personnel exposure and a more controlled locking operation due to the flexibility of the crane’s wire rope.

Use of a single network of beacons during some operations: To reduce the fixed times during certain operations, a new approach was implemented which involved the use of a single network of beacons. This approach was specifically employed during short operations, such as managed pressure operations decisions and installations. The configuration used for these operations was simplified with reduced redundancy, consisting of only four beacons plus one additional backup beacon.

By utilizing a single network of beacons, the system was able to streamline the process and reduce the time required for these short operations. The use of a simplified configuration with reduced redundancy also contributed to the overall efficiency of the process, making it easier to manage and reducing the potential for errors.

The implementation of this new approach enabled the team to carry out these short operations more quickly and with greater precision, helping to reduce the overall time required for the project. This allowed the team to complete the project more efficiently, meeting deadlines and staying within budget while also ensuring the safety of all personnel involved.

RIH strategies: The process of Running in Hole (RIH) involves the placement of the Bottom Hole Assembly (BHA) and drill bit into the wellbore. Conventionally, the filling of BHAs involves manual intervention, which can be a time-consuming process. To overcome this challenge, the strategy of using special automatic filling valves in the BHAs was implemented. This approach ensured a reduction in the frequency of draining the switching tank and, as a result, saved considerable time during maneuvering and coating operations.

It is important to mention that the use of automatic filling valves implied foregoing tests on the BHA tools. However, before implementing this strategy, the risk was evaluated and accepted based on the failure rate of the tools. While the risk of failure always exists in any drilling operation, this strategy proved to be effective in reducing fixed times associated with RIH. The implementation of this strategy can be seen as a key contributor to the reduction of fixed times in the drilling process. By reducing the time taken for RIH, overall drilling efficiency is improved, enabling quicker completion of projects and, therefore, reducing costs. The success of this strategy is a testament to the importance of evaluating risks and making informed decisions to optimize the drilling process.

Use of Dual Gradient Mud Cap Drilling (DGMCD) instead of MPD: Fixed time reduction is an essential aspect of efficient drilling operations, and one approach that can be used to achieve this is the use of Dual Gradient Mud Cap Drilling (DGMCD) instead of Managed Pressure Drilling (MPD) in the event of total circulation losses. The adoption of DGMCD is a strategy that eliminates the need to install and test the MPD system after the BOP maneuver. This translates into significant savings, as this process typically takes more than a day to complete. DGMCD is a drilling technique that involves the use of two mud gradients to maintain pressure balance in the wellbore. The technique utilizes a low-density fluid in the annulus and a high-density fluid in the drill pipe, creating a cap of mud that mitigates pressure surges and helps control circulation losses. By using this technique, drilling operations can be more efficient, and the need for additional equipment, such as MPD systems, can be eliminated, which can save valuable time.

The decision to use DGMCD instead of MPD also eliminates the need to conduct tests on the MPD system, which would have taken additional time. While the use of DGMCD may come with its own set of risks, such as tool failure rates, these risks were evaluated and accepted based on historical failure rates. Overall, the use of DGMCD instead of MPD is an effective approach to reducing fixed times during drilling operations.

BOP equipped with test ram: The implementation of a BOP equipped with a test ram was a significant step in reducing fixed times during drilling operations. Previously, when testing the BOP, an additional maneuver was required to seat and withdraw the test plug, which was both time-consuming and increased the risk of human error. However, with the BOP test ram, it became possible to test the BOP with the BHA still in the annular space, without the need for additional maneuvers. This eliminated the need for extra time and effort, while also reducing the risk of accidents and errors during the testing process. The test ram also made it possible to test the BOP more frequently and easily, improving safety and efficiency during drilling operations. As a result, the use of the BOP equipped with a test ram has been widely adopted by drilling operators worldwide, leading to further improvements in safety and cost-effectiveness.

3.5 NPT (Non-Productive Time) Mitigation

BOP reliability: BOP reliability is a critical aspect in the prevention of non-productive time (NPT) during drilling campaigns. To mitigate the risk of downtime due to BOP failure, a comprehensive approach to BOP reliability was adopted. This approach involved the use of real-time monitoring for component health analysis and predictive maintenance. By constantly monitoring the BOP's components, it was possible to identify any potential issues before they developed into critical problems that could lead to NPT.

To further enhance BOP reliability, all intermediate wells were planned in advance in terms of spare parts, man hours, and scope of work. The operator and support engineers of the drilling contractor were onboard to ensure that a high standard of BOP performance was maintained throughout the drilling campaign. This proactive approach ensured that any potential issues were addressed before they became major problems, and that the

BOP was always ready for use when needed.

By focusing on BOP reliability, the drilling campaign was able to operate more efficiently, with fewer interruptions due to equipment failures. This not only saved time but also reduced costs associated with repairs and replacements. In addition, the improved reliability of the BOP enhanced safety by reducing the risk of blowouts and other incidents that could have serious consequences. Overall, the comprehensive approach to BOP reliability was a key factor in mitigating NPT during the drilling campaign.

Asset Integrity Program: The Asset Integrity Program played a crucial role in mitigating NPT during the drilling campaign by ensuring the reliability and integrity of critical equipment and systems on the drilling platform. This program was designed to balance serviceability, reliability, and availability, and was aimed at ensuring that scheduled maintenance was performed at the optimal time between operations to minimize downtime and maximize equipment availability.

Real-time monitoring was used to analyze the health of critical components and predict any potential failures, allowing for proactive maintenance and repairs. This approach helped to prevent unexpected downtime and reduce the likelihood of equipment failure during operations.

The program also involved the planning and management of spare parts, man-hours, and scope of work for all intermediate wells, ensuring that the necessary resources were available when needed. The drilling contractor and operator worked together to develop a comprehensive maintenance schedule that would keep critical equipment and systems running at peak performance throughout the campaign.

As a result of this program, the drilling unit was able to achieve a high percentage of uptime for critical equipment and systems, starting at around 95% and gradually increasing to 99% over the course of the campaign. This level of reliability and availability was essential for delivering wells with a high standard and minimizing NPT.

Process Safety: The partnership would have failed had it not been extended on the process safety side. As mentioned, the identification and mitigation of risks were key points that were looked at by the partnership and the security of the process translated into having better tools, a better understanding of what was possible and, therefore, better procedures. Examples of this were the implementation of software to standardize and reduce human interference in the BOP test, enabling greater reliability in the data and also better quality of the test itself, optimizing the use of the maneuvering tank during runs whenever the well was not exposed to training as well as training sessions on sharing learnings with offshore platform crew from previous process safety incidents.

Real-time monitoring: Process safety is an essential aspect of any drilling campaign, and the partnership's focus on identifying and mitigating risks helped ensure the success of the project. One important aspect of process safety was the implementation of software to standardize and reduce human interference in the BOP test. This not only enabled greater reliability in the data but also improved the quality of the test itself. In addition, the partnership optimized the use of the maneuvering tank during runs when the well was not exposed to training, reducing the likelihood of accidents and increasing safety.

The partnership also recognized the importance of learning from previous process safety incidents, and training sessions were conducted to share these learnings with offshore platform crew. This proactive approach to process safety helped to prevent incidents from occurring in the first place.

Another key aspect of the partnership's approach to process safety was the focus on having better tools and a better understanding of what was possible. By investing in the right tools and equipment, the partnership was able to ensure the security of the process and minimize the risk of accidents. This approach also helped to improve the efficiency of the drilling campaign, as better tools and equipment meant that operations could be carried out more quickly and safely.

The partnership's focus on process safety was a critical factor in the success of the drilling campaign. By identifying and mitigating risks, investing in the right tools and equipment, and sharing learnings with offshore platform crew, the partnership was able to minimize the risk of accidents and ensure that the project was completed safely and efficiently.

3.6 Safety and Preparation

Reinforcing the safety culture: To reinforce the safety culture on the drilling platform and promote a shared understanding of safety, the main partners of the drilling campaign implemented various measures. One of the key actions taken was to establish a clear and concise safety policy that was communicated to all crew members on the platform. The policy emphasized the importance of safety and provided guidelines for safe work practices.

Additionally, safety training programs were implemented to educate crew members on the importance of safety and how to work safely on the platform. The training covered a range of topics, such as hazard identification, risk assessment, personal protective equipment (PPE), emergency response, and incident reporting. To encourage a positive safety culture, the partners also implemented a safety incentive program that recognized and rewarded crew members for good safety performance. The program was designed to promote a proactive approach to safety and encourage crew members to report hazards and near-misses.

Furthermore, regular safety meetings were held to discuss safety issues and share best practices. These meetings provided a forum for crew members to discuss safety concerns and suggest ways to improve safety performance.

The partners of the drilling campaign recognized that reinforcing the safety culture on the platform was critical to achieving a safe and successful campaign. By implementing a range of measures to promote a shared understanding of safety and encourage safe work practices, the partners were able to establish a strong safety culture that contributed to the success of the campaign.

Preparation for the project: Preparation for the project involved several key steps to ensure a successful and safe drilling campaign. One of the first steps was setting high standards and expectations for safety culture during the bidding process. The operator made it clear that safety would be a top priority throughout the project, and potential contractors were evaluated based on their safety records and practices.

After the contract was signed, face-to-face engagements took place between management teams from both the operator and the drilling company. These meetings were critical in clarifying roles and responsibilities, discussing safety protocols and procedures, and building trust between the two organizations. The meetings also allowed for the identification of any potential cultural conflicts or differences between the crews and provided an opportunity to address them before the drilling campaign began.

In addition to these meetings, a comprehensive safety plan was developed and implemented, which included identifying potential hazards and risks, as well as developing mitigation strategies and emergency response plans. The safety plan was continuously reviewed and updated throughout the project to ensure that it remained relevant and effective.

Training and development programs were also implemented to ensure that all crew members were properly trained and qualified to perform their duties safely and efficiently. This included training on the use of safety equipment and procedures, as well as emergency response drills and simulations. The preparation for the project focused heavily on building a strong safety culture and ensuring that all aspects of the drilling campaign were aligned with that culture. By setting high standards, clarifying roles and responsibilities, developing comprehensive safety plans, and providing training and development opportunities, the project was able to minimize risks and ensure a safe and successful drilling campaign.

Transition Documents: Transition documents are critical in ensuring a smooth and safe transition between different phases or stakeholders of a project. In this case, the contractor's HSE and Drilling Engineering teams performed a gap analysis between key HSE documents, such as the HSE Plan, HSE Case, Operating Procedures, and Emergency Response Plan, to ensure that they were aligned with the operator's expectations and requirements for the drilling campaign. This analysis allowed the teams to identify gaps in the existing documents and create new procedures where necessary to meet specific needs.

The Transition Document addressed key concerns for the campaign, such as Change Management, Work Permits, and Well Control. These concerns included issues related to authority to issue and approve, risk assessment and monitoring, controls in place, communication, SIMOPS (Simultaneous Operations), SOOB (Start of Offshore Operations), hot work, and H2S prevention and management. The document was revised as opportunities and lessons were learned throughout the project to ensure continuous improvement. Collaborative work was also essential in making possible the application of the DGMCD, which required a set of new procedures within the drilling contractor's HSE standards. This involved close coordination between the operator and the drilling contractor to ensure that the new procedures were properly integrated and aligned with the overall safety culture and standards of the project. Overall, the development of the Transition Document and the collaborative efforts to implement new procedures demonstrate a commitment to reinforcing the safety culture and ensuring that all stakeholders are aligned and working towards a common goal of safe and successful drilling operations.

Two new ways to work and improve safety: The Assist and Assure initiative implemented during the drilling campaign focused on leadership skills, preparation for work, and transition to work meetings. The technique aimed to protect people and assets from common causes of incidents by constantly assessing people's behavior in their work routine. This approach facilitated the maintenance of a safety culture on board, and the evaluation of controls ensured that the crew adhered to the highest safety standards.

The Design of Work technique, inspired by sports, was another initiative implemented to improve safety. It involved creating a visual representation of the job, showing the position and expected movements of people performing the task. This technique was simple yet powerful in standardizing the performance of the four crews and ensuring safer task execution. By providing a clear and concise understanding of the task requirements, the Design of Work technique reduced the potential for misunderstandings and errors, and over time, improved performance and safety in routine and repetitive operations.

These two initiatives were new ways of working that improved safety during the drilling campaign. By fostering a safety culture through constant assessment and evaluation, and standardizing the performance of tasks through the Design of Work technique, the drilling platform became a safer environment for all crew members.

Preparation for action - Goal Zero: Preparation for action started well before the drilling campaign began, with the goal of achieving Goal Zero, which means no harm to people, the environment, or assets. The operator made it clear to all parties involved that Goal Zero was the ultimate objective, and it was expected that everyone would take ownership of this objective. The management of the companies involved in operations, at all levels, reinforced the right to stop any work that did not comply with safety protocols, thereby ensuring the Authority to Stop. The concept of Goal Zero was the unifying message that guided the team throughout the drilling campaign. It was embedded in the company culture, and every employee was encouraged to take ownership of the objective. To achieve this, the management of the companies involved reinforced the need for constant vigilance in identifying and mitigating potential hazards that could compromise the safety of the crew, the environment, or assets.

The ”Authority to Stop” was also emphasized as a vital tool to prevent incidents. Any employee who identifies an unsafe situation is encouraged to use this right to stop work immediately until the situation is resolved. This approach helps to prevent incidents before they occur, promoting a proactive safety culture. The team was trained to recognize the warning signs of potential incidents and to take action immediately to prevent them. The team also received regular updates on the latest safety procedures and best practices to keep them up-to-date and aware of emerging risks. The implementation of Goal Zero and Authority to Stop promoted a culture of safety that extended beyond the drilling campaign. The team realized that they were responsible for maintaining this culture not only during the drilling campaign but also in their daily lives. Thus, Goal Zero and Authority to Stop became ingrained in the company culture, ensuring that safety remained a top priority.

All people participating with Alert cards: The Alert Cards were an essential tool to enhance safety culture on the drilling platform. They allowed the crew to report any unsafe conditions or behavior, which could potentially cause incidents or accidents. The agreement to have at least one card per day per person onboard every day, regardless of their role, helped to ensure that everyone was aware of the importance of reporting any unsafe conditions. The data collected through these Alert Cards were then monitored and analyzed by the HSE and Drilling Engineering teams to identify trends and patterns that needed to be addressed. Over time, the closure of the items reported through the cards by the crew contributed to increasing safety awareness and reinforcing the safety culture on board.

It was a continuous improvement process that involved the entire crew, and it proved to be an effective way of engaging everyone in the safety effort. The constant monitoring of the Key Performance Indicator (KPI) related to Alert Cards helped to identify areas that needed improvement and provided a clear picture of the effectiveness of the safety measures in place.

The use of Alert Cards and the agreement to have at least one card per day per person onboard every day were important steps in enhancing safety culture on the drilling platform. It encouraged the crew to be more vigilant and proactive in identifying and reporting potential hazards, and it allowed the management to monitor and address the safety concerns effectively.

Safety workforce: The presence of safety managers and RSTCs (Rig Safety and Training Coordinators) on board the drilling platform is crucial to ensuring that crew members are following safety protocols and procedures. These personnel are responsible for showing crew members the correct way to proceed safely and being constantly vigilant for potential safety hazards. To further reinforce safety culture, the operator of the drilling platform provided two HSE (Health, Safety and Environment) representatives to work alongside the drilling contractor's teams. These representatives worked closely with the crew to assist with incident reporting, behavior assessments, safety monitoring, and implementation of pending safety actions. The presence of these representatives helped to increase the effectiveness of the HSE process implemented on the platform, as they were able to provide additional support and guidance to the drilling contractor's team. Having an open and collaborative attitude was key to the success of this approach, as it allowed for effective communication and cooperation between the operator and the drilling contractor. By working together towards the common goal of improving safety on the platform, the team was able to achieve a high level of safety performance and minimize incidents during the drilling campaign.

HSE Case and communication: The HSE Case is a critical document that outlines the major accident hazards and their associated risks on the drilling platform. Communication regarding the HSE Case and its implementation is crucial to ensuring the safety of all personnel on board. To facilitate this, the drilling contractor and the operator ensured that regular meetings were held to discuss the HSE Case and its practical application. They also made sure that all personnel were aware of the HSE Case and its importance in maintaining a safe working environment.

To further improve communication and ensure that the HSE Case was being followed correctly, BowTies were used as a visual tool to help identify and assess potential hazards and associated barriers. The individuals responsible for each barrier were informed of their roles and responsibilities, and their knowledge and experience were harnessed to ensure that barriers were maintained and that risks were mitigated.

In addition to this, personnel change management was implemented at critical positions to ensure that only properly trained and qualified personnel were responsible for maintaining and monitoring barriers. Any deviations from the established procedures needed to be approved by both the operator and the drilling contractor. One significant breakthrough achieved in this project was the direct communication between the drilling contractor and third parties responsible for the barriers. The operator authorized and supported the drilling contractor to communicate directly with these third parties under the terms of the contract. This clear communication channel helped to reinforce the drilling contractor's ultimate responsibility for maintaining the maximum allowable hydrocarbon barriers and further improved the overall sa fety culture on the platform.

Implementation of Assist & Assure: Safety culture depends on the example of immediate supervision and the way these leaders communicate. Any security program to succeed must address leadership skills. People focused on their work is a safety and productivity requirement. To achieve this state of readiness, a technique was implemented using a series of meetings called transition to work. The idea behind this is to increase alertness, bring everyone into the conversation and check knowledge of the task at hand. Green hats - new people on board or at work - are given extra care with the support of a tutor. After leadership skills and focus on work comes the third requirement for successful work: identifying, in the Tool Box Talk, problems with planning, adequate communication, location and tools according to standards, implemented Lockout/Tagout and contingency plan. This outlines the seven steps to safe working. Any non-compliance must be corrected before starting work.

Once all three components are in place, the need for verification is implemented by a checklist being applied by one of the HSE staff onboard and subsequently having the results reviewed during a safety meeting. The identified gaps indicate points for improvement that could become a security problem, thus serving as a leading indicator of incidents.

It is also desirable to follow up on the causes of previous incidents in the sector. To this end, weekly safety focus areas have been established with the aim of raising awareness of the selected theme of the week. In association with a checklist to help identify gaps to be filled.

These two checks serve as tools for coaches to provide actionable feedback on the three initial components. It is the closure of the PDCA loop.

Cadence in Safety Programs - key feature to improve safety culture: Cadence in Safety Programs refers to the regularity and frequency of safety meetings, training sessions, and other safety-related activities. It is a key feature in improving safety culture as it ensures that safety is a constant and integral part of daily operations.

Regular safety meetings provide a forum for discussion, feedback, and the sharing of ideas and best practices. These meetings should involve all interested parties, including line managers, HSE staff, trainers, and contractor leaders, to ensure that everyone is on the same page and that all issues are addressed.

During these meetings, incidents should be reviewed, analyzed, and discussed to identify the root cause and possible corrective actions. Best practices should be presented and shared, and plans for future safety events should be discussed. Gap analysis and possible closure routes should also be evaluated and addressed to ensure that all safety issues are being addressed and that the safety program is effective.

By establishing a regular cadence of safety meetings and activities, a culture of safety is fostered, and everyone is engaged in the process. This helps to create a sense of ownership and responsibility for safety, which ultimately leads to a safer working environment.

Safety Campaigns - Fast Way to Close the Gaps: Safety campaigns are a way to reinforce the importance of safety within the workplace and maintain a constant awareness of potential risks. These campaigns involve regular activities and training sessions aimed at engaging employees and promoting a culture of safety. By focusing on specific topics or hazards, such as personal protective equipment, hazard identification, or fall prevention, safety campaigns encourage employees to think more critically about their work and how to do it safely.

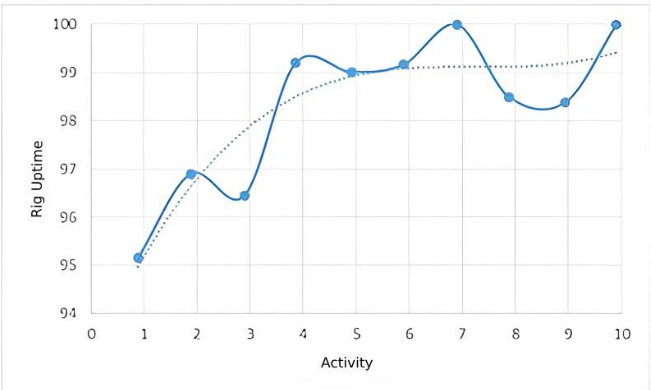
In this project, safety campaigns were used as a tool to identify gaps in the existing safety culture and to quickly close them. These campaigns involved short, targeted messages and activities aimed at specific groups of workers or hazards. For example, a campaign focused on fall prevention may include activities such as tool box talks, hazard assessments, and training on proper use of fall protection equipment.

The use of safety campaigns was an effective way to engage workers and promote a culture of safety. By making safety a top priority and emphasizing its importance through regular training and awareness activities, employees were more likely to pay attention to potential hazards and take action to mitigate them. Furthermore, the use of safety campaigns allowed for rapid identification and resolution of safety issues, helping to maintain a safe working environment throughout the project.

4 RESULTS AND ANALYSIS

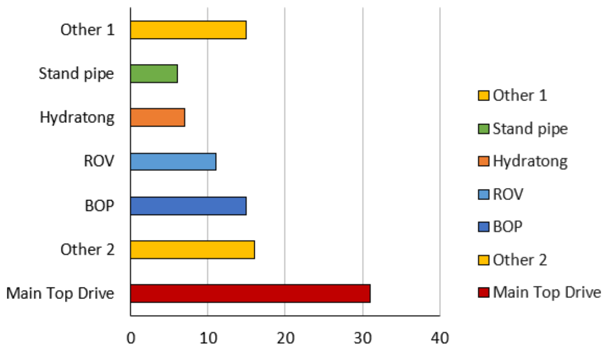
As observed in Figure 8, the drilling unit started with an uptime of around 95%, a value determined based on our analysis of the initial phase of the campaign. This uptime is considered reasonable for a new campaign and relationship between the company and contractor, it was able to flatten in an uptime of about 99% over the remaining activities. Equipment breakdown demonstrates that most of the downtime was associated with the main top drive and BOP as can be seen in figure 9, mainly because of the fundamental role that such pieces of equipment have in the critical path of the operation.

Figure 8: Rig's equipment downtime breakdown



Source: (Own work)

Figure 9: Drilling Rig Uptime during the 10 different sequential activities performed during the campaign (total of 16 months). It included drilling, completions and managed pressure operations. interventions.



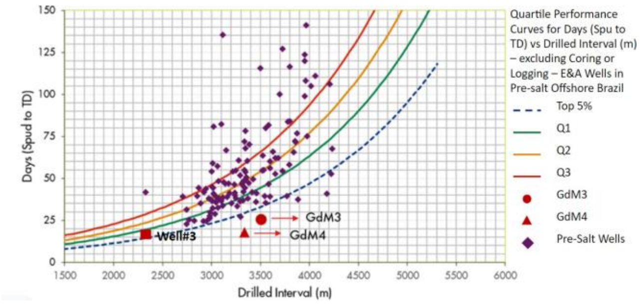
Source: (Own work)

Very high equipment uptime is instrumental in reducing the drilling time, therefore, the partnership focused on NPT mitigation during the campaign. The partnership extended its focus to process safety and real-time monitoring to improve its NPT mitigation efforts. On the process safety side, the partnership aimed to identify and mitigate risks better. This was achieved by deploying software to standardize and reduce human interference in BOP tests, optimizing the use of the trip tank during runs, and conducting training sessions for the rig crew offshore. The partnership also provided training on well control to front-line barrier managers before the campaign. Regarding real-time monitoring, the partnership tracked various KPIs to identify opportunities for improvement. The RTOC played a crucial role in enabling this tracking. The drilling contractor and the Integrated Wells Services provider both provided data and dashboards, allowing the team to monitor the operations from different angles and go into detail for specific operations such as BOP running and BHA running. This data fed most of the engagements involving the continuous improvement cycle in the PDCA.

Figure 10, provides the benchmarking visualization of the pre-salt wells drilled in the Pre-salt Cluster and the achievements of the GdM4 well drilled as part of the campaign and the potential savings when compared to the drilling time of most wells in the area. All four wells drilled were within the top 5% percentile with the GdM4 becoming the fastest pre-salt well ever drilled with its 18 dry-hole days mark when wells with the same length would be considered Top Quartile when delivered in 40 days. The total drilling time was approximately 17 days, hence total cost was significantly optimized. The total drilling time of approximately 17 days for the GdM4 well represents a significant optimization of the drilling process, and it is important to note that this optimization directly translated to cost savings. By reducing the drilling time, the total cost of the well was significantly optimized, demonstrating the importance of efficient drilling practices in the oil and gas industry. These results highlight the benefits of using the DID-PDCA methodology in drilling operations, and provide a strong case for further implementation of this approach in the industry.

There are potential benefits of applying the DID-PDCA approach to other pre-salt operations, it may have the potential to improve operational efficiency and optimize costs by providing a structured framework for continuous improvement. The approach involves identifying areas for improvement, designing and implementing changes, measuring their effectiveness, and making further adjustments as necessary. By following this cycle, it may be possible to identify opportunities for reducing drilling time, increasing safety, and improving overall performance. Additionally, by incorporating lessons learned and

Figure 10: Time versus depth scatter plot for GdM3 and GdM4 well from Spud-in until TD for different wells in the Pre-Salt cluster. For the GdM4 pre-spud, coring, logging and abandonment were purged.



Source: (Own work)

best practices into future operations, it may be possible to further optimize performance and drive long-term success. However, each operation is unique and may require its own customized approach, hence, it is important to carefully consider the specific context and goals before implementation.

There are some key issue that must be kept in mind if this approach is to be adopted. Firstly, it is important to have a clear understanding of the objectives and goals of the operation, and to ensure that the approach is tailored to meet those specific needs and the adoption of the DID-PDCA methodology requires a strong commitment from all parties involved. Operators must be willing to invest the necessary time, resources, and effort to implement the approach successfully. The DID-PDCA methodology is an iterative process that requires constant monitoring, evaluation, and improvement. Operators should be willing to review and update their processes continually to ensure they are meeting their objectives. Collaboration is a critical factor in the success of the DID-PDCA approach. Operators should work closely with their contractors, service providers, and other stakeholders to ensure that everyone is aligned with the same goals and objectives. Collecting and analysing data is crucial to the success of the DID-PDCA approach. Operators must be able to gather and analyse data on their operations to identify areas for improvement continually. Safety is a top priority in the oil and gas industry, and operators must ensure that safety considerations are integrated into every aspect of their operations. The DID-PDCA methodology can help operators identify potential safety hazards and implement measures to mitigate risks. Overall, the key issues to be observed by other operators wishing to adopt the DID-PDCA approach include commitment, continuous improvement, collaboration, data collection and analysis, and a focus on safety. By following these guidelines, operators can improve their operations, optimize costs, and achieve their goals more efficiently not only in pre-salt but generally.

5 DISCUSSION

The dissertation focused on the application of the DID-PDCA methodology in drilling operations in the Brazilian pre-salt basins. The results obtained demonstrated the effectiveness of this approach in reducing drilling time, optimizing costs, and improving operational efficiency. The partnership between the company and the drilling contractor played a crucial role in achieving these outcomes.

The analysis of the drilling unit's equipment downtime breakdown revealed that the main top drive and blowout preventer (BOP) were responsible for most of the downtime. These components are critical in the operation's critical path, highlighting the need for proper maintenance and effective troubleshooting strategies. By addressing the issues associated with these components and improving equipment uptime, the drilling unit was able to achieve a significant reduction in drilling time.

To further optimize drilling operations, the partnership focused on non-productive time (NPT) mitigation. The implementation of process safety measures, such as standardized BOP tests and optimized trip tank utilization, helped in identifying and mitigating risks better. Additionally, training sessions for the rig crew and front-line barrier managers enhanced well control practices and overall safety awareness. Real-time monitoring, facilitated by the use of data and dashboards provided by the drilling contractor and Integrated Wells Services provider, allowed for continuous improvement efforts based on key performance indicators (KPIs).

The success of the DID-PDCA approach provides a strong basis for its further implementation in the industry. By following the iterative cycle of identifying areas for improvement, designing and implementing changes, measuring their effectiveness, and making further adjustments as necessary, operators can continuously enhance operational efficiency and optimize costs. However, it is essential to recognize that each operation is unique and may require a customized approach that aligns with specific objectives and goals.

6 CONCLUSION

The dissertation has yielded significant findings that demonstrate the effectiveness of the DID-PDCA methodology in drilling operations within the Brazilian pre-salt basins. The partnership between the operator and the drilling contractor emerged as a pivotal factor in achieving remarkable improvements in drilling time, equipment uptime, and overall operational efficiency. The application of process safety measures, real-time monitoring, and continuous improvement efforts based on data-driven insights were identified as key drivers of success.

The results underscore the potential benefits of adopting the DID-PDCA approach in other pre-salt operations. By implementing a structured framework for continuous improvement, operators can identify areas for enhancement, optimize drilling time, enhance safety, and elevate overall performance. Collaboration, commitment, data collection and analysis, continuous improvement, and a strong focus on safety emerged as crucial considerations for successful implementation.

The findings presented in this dissertation provide a compelling case for the widespread adoption of the DID-PDCA methodology in drilling operations. By embracing this approach, operators in the oil and gas industry can enhance operational efficiency, optimize costs, and achieve their goals more effectively. The continuous pursuit of excellence through the DID-PDCA methodology can drive long-term success and ensure the industry's continued advancement in the pre-salt basins and beyond.

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