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Digital technology adoption, sustainability, and well construction delivery in oil and gas industry: Critical review of digital technology

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Abstract

The integration of digital technologies in the oil and gas sector is reshaping the sustainability and efficiency of well construction operations. This review critically examines the role of technologies such as artificial intelligence (AI), machine learning, cloud computing, digital twins, and the Internet of Things (IoT) in optimizing planning, drilling, and completion processes. By leveraging these technologies, companies can enhance resource utilization, improve decision-making, and align operations with sustainability goals. The study identifies significant challenges to adoption, including high implementation costs, regulatory uncertainties, and workforce upskilling requirements. Drawing on case studies and current literature, the findings reveal that digital transformation not only boosts operational efficiency but also supports environmental stewardship and economic resilience. This paper provides actionable insights for industry stakeholders seeking to achieve sustainable well construction through strategic digital technology integration.

Key Words: Digital Technology Adoption; Internet of Things; Well Construction; Artificial Intelligence; Machine Learning

1. Introduction

Well construction involves the drilling and development of a subsurface well to fulfill specific functions, such as extracting hydrocarbons, accessing geothermal energy, storing waste, or gathering geological samples. This multifaceted process demands meticulous planning, precise execution, and continuous optimization to ensure success. Key operations in well construction include site preparation, drilling, casing, cementing, and completion, each of which plays a vital role in maintaining well integrity and operational efficiency. Gurtej et al. (2022) describe well construction as a complex, multi-step process requiring informed decision-making at each stage. However, human factors, such as situational awareness and biases, often influence these decisions, leading to operational inefficiencies and safety or environmental concerns. Current methods and tools monitor well activities but lack the capability to evaluate potential action sequences or determine the optimal course of action. Challenges in Drilling Operations. Drilling, a cornerstone of well construction, is inherently unpredictable and costly due to the geological complexity deep beneath the Earth's surface. This complexity introduces uncertainty into operations, creating safety risks and requiring close monitoring of equipment and process variables. Failures in any stage of the drilling process, whether in equipment or execution, can lead to non-productive time (NPT) and substantial cost increases. The catastrophic blowout of the Macondo well in the Gulf of Mexico in 2010 (Griggs, 2010) serves as a stark reminder of the potential consequences of wellbore failures and well control issues. While monitoring remains critical for ensuring safety and efficiency, it must be complemented by real-time decision-making tools. Currently, decisions rely heavily on human expertise, with no robust systems for

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tracking and analyzing scenarios in real time, significantly reducing the likelihood of optimal responses. Advancements such as directional and horizontal drilling have enabled access to previously unreachable reservoirs, enhancing resource recovery (John, 2024). Measurement-While-Drilling (MWD) and Logging-While-Drilling (LWD) technologies provide real-time data, supporting informed decision-making and improving operational outcomes. Ensuring stability and longevity casing and cementing are essential for maintaining wellbore stability and preventing unwanted fluid movement. Research into advanced materials and techniques, such as expandable casing and nano-modified cement, shows promise for addressing challenges like casing deformation and cement integrity. These innovations aim to enhance well reliability and longevity, further improving the sustainability of well construction practices. Optimizing well construction has become a focal point for reducing costs, mitigating risks, and enhancing efficiency. Mathematical models and computational methods have been employed to develop numerous optimization strategies. Digital technologies, including artificial intelligence (AI), machine learning, and real-time data analytics, are revolutionizing well construction by offering advanced solutions for planning, monitoring, and decision-making. This paper explores the integration of digital technologies into oil and gas well construction, highlighting their potential to improve delivery, efficiency, and sustainability in the industry.

2. Methodology

The study relied on residual data sourced from a variety of platforms, including conference proceedings, textbooks, peer-reviewed journal articles, unpublished materials, and reputable websites. This comprehensive approach was designed to cover broad areas of interest, focusing on the adoption of digital technologies, sustainability practices, and strategies for achieving efficient well construction delivery in the oil and gas industry.

2.1. The Adoption of Digitalization Technology in Oil and Gas Industry

The oil and gas industry has amassed extensive datasets over decades, yet managing and utilizing these datasets effectively remains a persistent challenge. In exploration, identifying high-value regions for investigation is increasingly critical. Advanced modeling and simulation techniques are essential for synthesizing structural data into actionable models. Similarly, operational efficiency in drilling and production demands advancements in areas such as pressure anomaly detection, energy management, asset maintenance, equipment automation, and safety protocols (Eswaran et al., 2023). Effective big data management is vital for maintaining competitiveness, particularly during the planning and field development stages. Enhancing field productivity throughout its lifecycle has the potential to significantly boost output. Over the last decade, the petroleum sector has undergone substantial digitalization, the process of converting analog data into digital formats. This shift addresses challenges such as managing massive datasets and optimizing operations. Since the Industrial Revolution, the oil and gas industry has been pivotal in global economic development, meeting demands for energy and transportation. Digitalization is now redefining industry boundaries. Amid challenges such as volatile crude oil prices, budget overruns, demands for climate transparency, and a shortage of skilled talent, digital technologies have enabled the sector to deliver tangible solutions.

According to the World Economic Forum (2017), digitalization has the potential to overcome significant barriers and create value for stakeholders. The International Energy Agency (IEA) estimates that adopting digital technologies could reduce production costs by 10–20% and increase technically recoverable reserves by over 5 billion barrels globally (IEA, 2017). "Big data" refers to datasets characterized by their vast size, complexity, and high-frequency aggregation, which traditional data processing tools cannot efficiently handle (Holdaway, 2014). These datasets, often measured in terabytes, petabytes, or even exabytes, present analytical challenges. For the oil and gas industry, inductive statistics and nonlinear system identification are crucial for managing large datasets. These methods enable the detection of correlations and the application of data-driven algorithms to predict behaviors in complex, multivariate reservoirs. Digitalization encompasses a wide range of technologies, including big data, the Internet of Things (IoT), advanced data analytics, and innovative business strategies. By transforming traditional business models, digitalization generates new revenue streams, enhances client engagement, and creates added value.

2.2. Historical Context and Digitalization's Evolution

Discussions about digitalization's potential to improve operations have been ongoing for decades. Since the 1980s, the oil and gas industry has integrated digital technologies to gain insights into reservoirs, optimize production, and ensure compliance with health, safety, and environmental (HSE) standards. These early efforts primarily aimed to enhance marginal operational efficiencies across global oilfields.

Despite its potential, the oil and gas industry has traditionally lagged behind other sectors, such as metallurgy, chemical manufacturing, and machinery, in adopting digital solutions (Gafurov et al., 2020). However, the discovery of large yet challenging-to-recover hydrocarbon deposits, such as those in the Arctic, has driven advancements in value creation and business model reform. Digital transformation of the supply chain, particularly for offshore projects, is now critical for maintaining competitiveness. The digitalization of the petroleum industry has revolutionized both upstream and downstream operations. By reducing downtime and nonproductive drilling time, the industry is advancing toward improved petroleum system management. Figure 1 illustrates the digital transformation of offshore supply chains, while Figure 1 depicts the capital-intensive processes in the oil and gas industry, categorized into upstream, midstream, and downstream segments.

- **Upstream Sector**: This involves the exploration and search for crude oil, natural gas, and other resources in fields, underground, or beneath the sea. Once promising discoveries are made, the production phase begins, encompassing drilling and operating the site.
- **Midstream Sector**: This stage focuses on the transportation, storage, and delivery of refined products to retailers, distributors, and other entities within the supply chain.
- **Downstream Sector**: This involves the purification, marketing, and distribution of usable products such as gasoline, diesel, and kerosene. Each sector faces unique challenges. In the upstream sector, drilling processes can be enhanced and expedited using artificial intelligence (AI) and machine learning techniques (Koroteev and Tekic, 2021). The downstream sector can benefit from digitalized supply chains, generating critical insights to improve distribution efficiency. By analyzing the vast datasets produced by digitalization, product delivery can be optimized (Gezdur and Bhattacharjya, 2017; Lima et al., 2016). The midstream sector, however, lags behind the others in digitalization. This lack of progress has significant implications, emphasizing the need for focused efforts to bridge this gap.

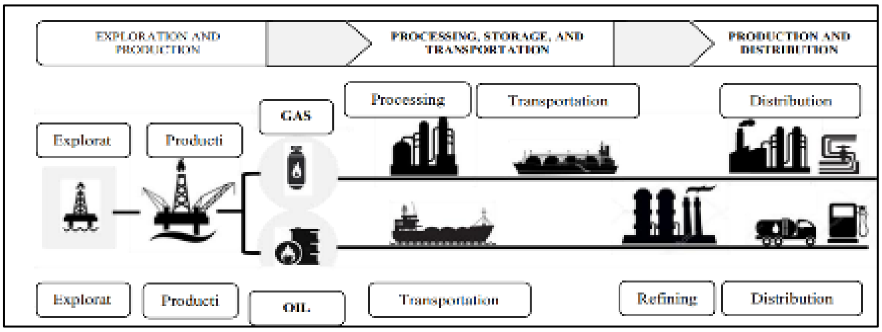

Figure 1 Supply Chain of Oil and Gas Enterprises

The oil and gas industry has embraced the power of big data to address its operational complexities and drive innovation. The constant generation of vast datasets has spurred the development of innovative technologies designed to streamline production processes. These tools enable the efficient acquisition, organization, and analysis of large volumes of data, fundamentally transforming industry practices.

In the context of the oil and gas sector, "big data" refers to the massive, complex datasets that challenge traditional analytical methods (Holdaway, 2014). The introduction of high-performance analytics has revolutionized the sector, enabling advanced problem-solving and data-driven decision-making. The petroleum system functions much like an ecosystem, with interdependent subsystems working cohesively. This system is marked by significant heterogeneity, sequence identity, and structural similarities. As Nimmagadda and Dreher (2013) emphasize, digitalizing the petroleum system requires a comprehensive understanding of these interrelationships. Multidimensional data configurations and metadata modeling play a crucial role in representing sedimentary basins and optimizing the system's vast datasets. Integrating diverse data sources into cohesive database structures facilitates advanced data mining and visualization. However, complex challenges often require the integration of multiple databases to derive actionable insights. One of digitalization's key advantages in the petroleum sector is its capacity to transform extensive and intricate datasets into valuable geological insights, enhancing exploration and production efficiency. As the global energy landscape shifts toward cleaner and more sustainable options, the oil and gas industry are adapting to address the challenges of an evolving energy mix. Digitalization supports this transition by improving access to diverse data sources, advancing exploration, and refining production processes. For example, string-matching algorithms now allow for the efficient identification of regions of interest, streamlining exploration activities.

Big data analytics has also simplified the previously time-intensive process of trend identification and ambiguous data analysis. Advanced algorithms now perform these tasks automatically, enabling geoscientific predictions that support informed decision-making. The availability of real-time data empowers companies to respond quickly to underperforming wells, reducing downtime and operational costs. Certain applications can solve complex problems within minutes, significantly accelerating operational processes and providing substantial benefits to oil and gas companies.

The integration of big data and digital technologies in the oil and gas industry has ushered in a new era of efficiency and innovation. By transforming vast datasets into actionable insights, these tools have not only enhanced operational capabilities but also positioned the industry to adapt to emerging energy challenges. As the sector continues to evolve, digitalization will remain a critical enabler of sustainable and efficient operations.

2.3. Role of Digitalization and Automation in Oil and Gas Well Construction

Digitalization and automation technologies are revolutionizing the oil and gas industry, particularly in the area of well construction. According to Haohan et al. (2023), the industry is undergoing a significant transformation driven by advancements in artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), and big data analytics. These cutting-edge technologies are being employed to enhance operational efficiency, profitability, and data-driven decision-making across the sector.

Drilling operations, a critical component of oil and gas well construction, represent a significant portion of overall well expenditures. Consequently, the adoption of technology-driven solutions is essential for ensuring safe operations, minimizing costs, and improving project outcomes. In an industry characterized by volatile markets and stringent regulations, the integration of digital and automation technologies is vital for maintaining competitiveness and achieving long-term sustainability.

2.4. Digitalization and Automation in Oil and Gas Well Construction

2.4.1. Optimized Well Planning and Design

Digital technologies simplify well planning and design by combining large databases of geological, geophysical, and engineering data. These datasets are analyzed by artificial intelligence (AI) and machine learning (ML) algorithms to generate optimal well trajectories, lowering risks such as formation damage or collisions with adjacent wells. A digital twin is a virtual representatgion of a wellbore that allows engineers to model different situations and optimize well design before drilling.2. Automated Drilling Operations

Automation technologies are transforming drilling operations, increasing safety and efficiency. Key advancements include:

Robotic Pipe Handling: Automated technologies remove the need for manual work and lower the danger of damage during pipe handling. Michael et al. (2022) stated that a robotic rig has successfully completed nine wells, with steady improvement since drilling began in August. Drilling connection times have improved by 28%, making the rig the third fastest in the fleet. Furthermore, the rig's casing running performance has improved by about 43%, bringing it on par with other high-performing rigs in the fleet. These activities are fully automated, resulting in consistent and predictable performance across all drilled wells. This is achieved without the need for human interaction to handle tubulars in the mast or on the rig floor. The operator, drilling operations team, rig engineering team, and controls and automation team all worked together to make this groundbreaking robotic rig a success. These teams collaborate to discover areas for improvement, with the goal of drilling more safely, quickly, and efficiently.

Smart Drilling Systems: Artificial intelligence (AI) uses real-time data from drill string and bottom-hole assembly sensors to optimize drilling parameters including weight-on-bit and rotation speed. This improves accuracy and reduces non-productive time (NPT) (Mokhatab et al., 2019). Maintaining formation pressure and avoiding kicks is crucial while drilling deep wells. This is accomplished by regulating the equivalent circulating density (ECD), which is especially critical in high-pressure, high-temperature wells and strata with narrow pressure windows, such as those with low pore and fracture pressures. However, current technologies for detecting ECD with downhole sensors are expensive and limited by operational problems such as harsh pressure and temperature extremes. To overcome these restrictions, Mohammed et al. (2023) created two novel models: ECDeffc.m (modified equivalent circulating density) and MWeffc.m (modified mud weight effective). These models use surface-drilling characteristics such as standpipe pressure, penetration rate, drill string rotation, and mud qualities to forecast ECD and mud weight (MW). The authors assessed the models using AI-driven techniques, demonstrating that they beat standard pressure-while-drilling (PWD) equipment in terms of accuracy. These models have considerable advantages since they may be used throughout well design and drilling operations to establish and monitor suitable mud weight and ECD. By removing the need for costly downhole equipment and commercial software, these models can save time and money. Furthermore, Nabors Drilling has implemented automated rigs outfitted with robotic systems and AI-powered controls, resulting in shorter drilling cycles and cheaper operational costs.

2.4.2. Real-Time Data Monitoring and Decision-Making

The use of Internet of Things (IoT) sensors in well construction gives real-time data on pressure, temperature, vibration, and torque. Data is supplied to centralized monitoring centers, enabling remote teams to make timely decisions. The essential tools were Supervisory Control and Data Acquisition (SCADA), which remotely monitors and controls drilling equipment, and drilling advisory systems, which provide actionable insights based on real-time analytics, thereby boosting decision accuracy.

2.4.3. Improved Well Integrity Management

Maintaining well integrity is crucial for both safety and envirhonmental preservation. Digital tools continuously monitor cementing, casing, and wellbore stability, assuring compliance with design parameters and lowering the danger of blowouts or leaks (Li et al., 2020).

Predictive Analytics: AI models use historical and real-time data to predict possible faults, allowing for proactive maintenance and risk avoidance.

2.4.4. Improved safety through automation

Automation decreases human exposure to high-risk jobs, improving safety during well construction. Autonomous rig operations, in which drilling rigs outfitted with automated systems handle repetitive and hazardous tasks such as tripping pipe or connecting drill strings, and wearable IoT devices, which monitor workers' health and environmental conditions and alert them to potential hazards (Fleming et al., 2021). For example, BP's use of wearable sensors on offshore rigs has led to significant incidence reductions.

2.4.5. Sustainable and Eco-Friendly Operations

Digitalization enhances sustainability in well building by eliminating waste and optimizing resource utilization. For example:

Efficient Drilling Fluid Management: IoT sensors continuously monitor and adjust drilling fluid parameters to reduce overuse and contamination.

Emissions Monitoring: Digital tools monitor emissions from rigs and other equipment to verify that environmental regulations are met (Perks et al., 2022).

2.4.6. Post-construction monitoring and maintenance.

Following well construction, digital tools continue to play an important role in monitoring well performance and guaranteeing long-term integrity. AI-powered software analyzes sensor data to optimize production and detect anomalies that may require action (Hyne, 2018).

Digital Well Files: Comprehensive digital records of well construction and operation promote collaboration and transparency, particularly during audits and decommissioning efforts. The benefits of digitization and automation in well construction are as follows: It achieves faster drilling cycles and less non-productive time; optimizes resource allocation and decreases maintenance costs; limits human exposure to high-risk operations; and reduces emissions, waste, and environmental impact.

2.5. Application Areas of AI in Drilling and Completion Engineering

Drilling and completion engineering have evolved into a sophisticated technological system governed by technical principles and processes that incorporate equipment, tools, and materials. Intelligent models are increasingly used in drilling engineering to address a variety of issues, including leakage, rate of penetration (ROP) prediction, well trajectory optimization, drilling risk warnings, cementing quality evaluation, fracturing process optimization, completion design, overall process optimization, and intelligent decision-making. In recent years, the most popular intelligent models have been artificial neural networks (ANN), fuzzy logic systems, genetic algorithms (FLSGA), support vector machines (SVM), particle swarm optimization, hybrid intelligent systems, and case-based reasoning. These models have showed promise in solving difficult engineering challenges by assessing and improving several factors at the same time.

Figures 2 and 3 depict the use of artificial intelligence technology in drilling engineering, demonstrating how AI integrates and evaluates all essential parameters to improve decision-making and operating efficiency.

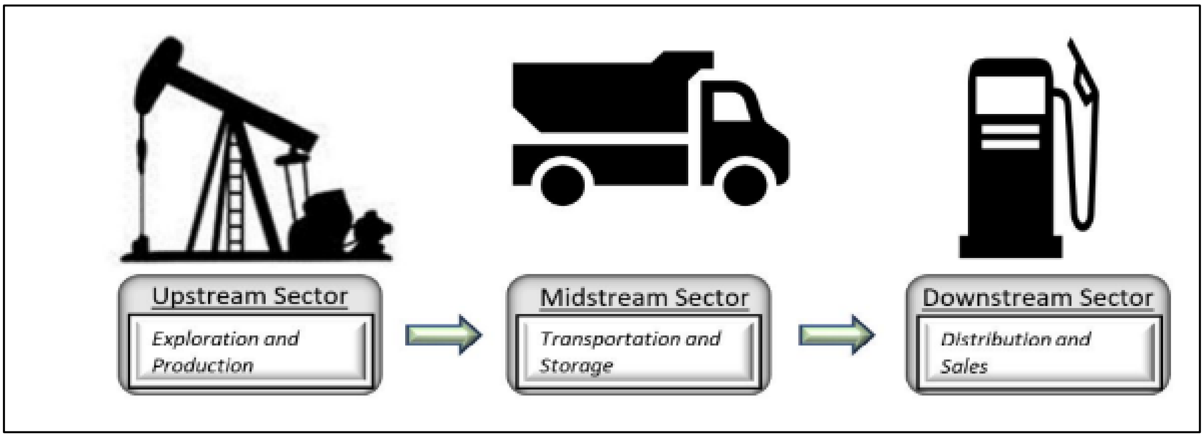

Figure 2 The three sectors of the Oil and Gas Industry

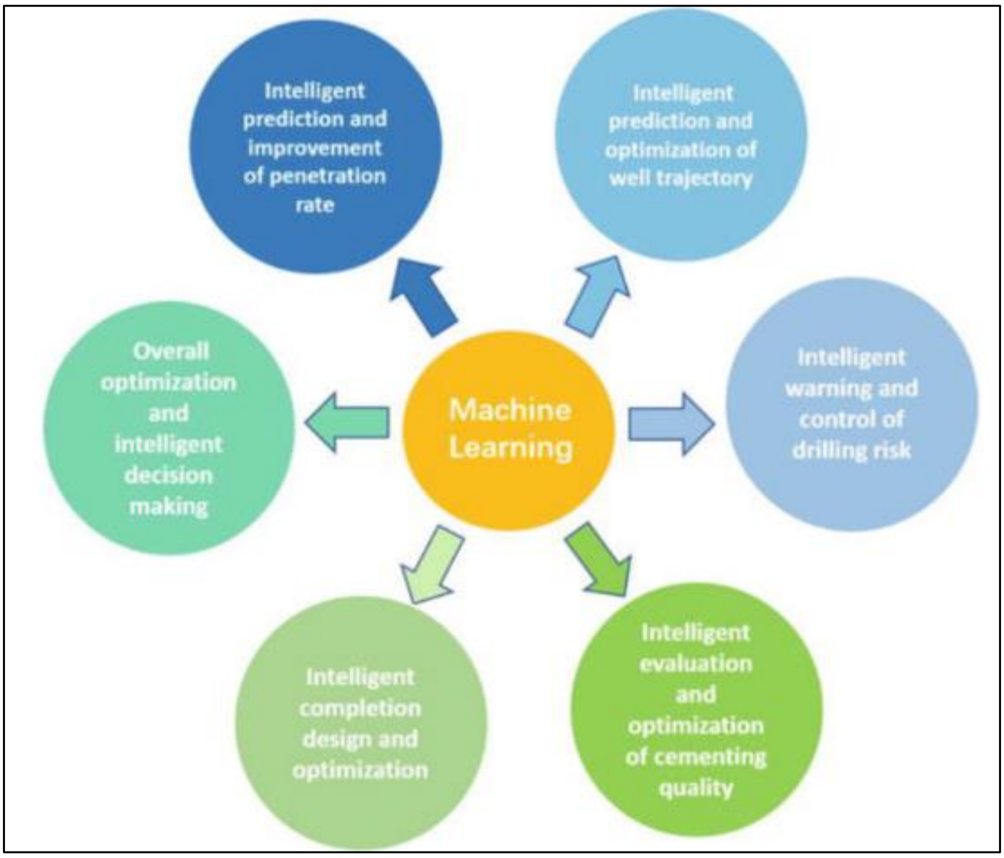

Figure 3 Covers all aspects of Drilling Engineering

2.5.1. Intelligent Prediction and Improvement of Penetration Rate

An increasing number of wells are being drilled in deep, hard, and abrasive rocks, resulting in high bit wear and slower drilling speeds. Predicting the drilling machine penetration rate is critical for optimizing drilling parameters such as data validation, mechanical specific energy reduction, bit life extension, and controllable factor adjustments (Banna et al., 2021). Many factors influence the mechanical penetration rate, and these can be classed as controlled or uncontrollable. Controllable factors are those that can be manually altered using specialist equipment and techniques, such as ground machine pump equipment, bit size, drilling fluid properties, bit weight, and rotation speed. Uncontrollable variables include drilled formation lithology, reservoir burial depth, and formation pressure (Hazbeh et al., 2021). Artificial intelligence algorithms can forecast the mechanical penetration rate of different drilling acceleration tools by taking into account drilling fluid density, drilling parameters, bit size, drilling acceleration instruments, and rock strength. This allows for the evaluation of each tool's operational effectiveness. Intelligent algorithms also provide a precise representation of the bottom hole environment, which aids in not only optimizing drilling parameters and increasing drilling speed, but also in detecting anomalous conditions and immediately preventing complex incidents, as illustrated in Figure 4.

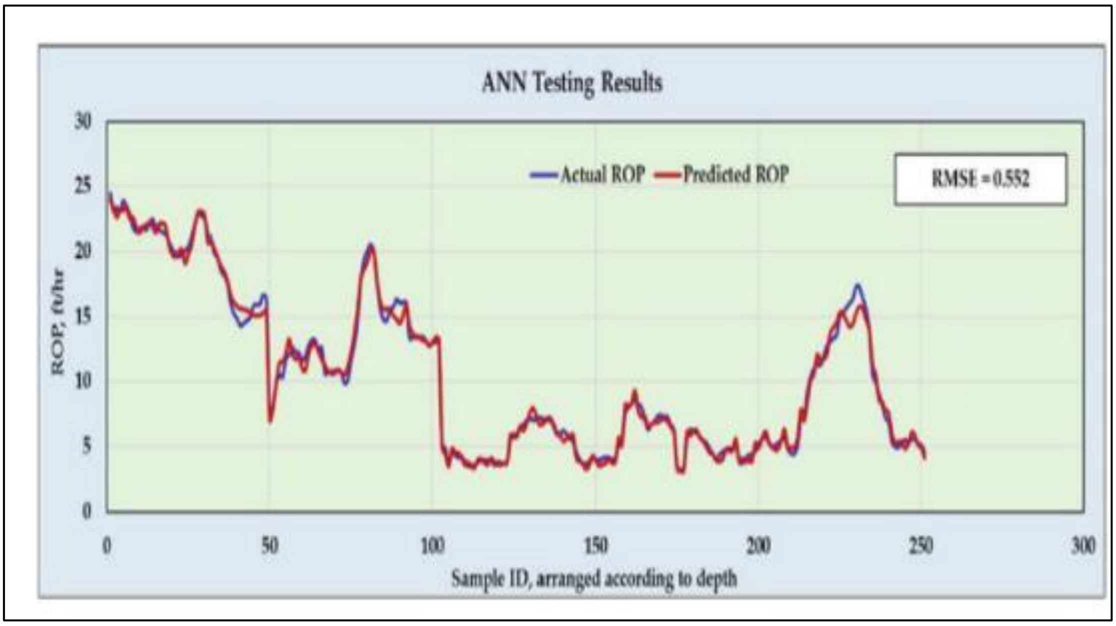

Figure 4 All areas of drilling engineering ROP prediction using the ANN technique for (A) training (750 data points) and (B) testing data (250 data points).

2.5.2. Intelligent Prediction and Optimization of Well Trajectory

Inclined, horizontal, and extended-reach wells are frequently employed to effectively develop unconventional reservoirs. However, due of the severe abrasiveness, anisotropy, and unpredictability of formation rocks, drilling trajectories can readily diverge from the intended course. Big data and artificial intelligence technology can be used to optimize the well trajectory before drilling starts. During the drilling process, real-time trajectory monitoring enables for deviation estimation and, as needed, steering parameter correction. This procedure creates a mapping link between important controllable parameters and their applications, making it easier to create control instructions and resulting in a closed-loop control system. Intelligent borehole trajectory design and real-time optimization are divided into multiple stages: intelligent borehole trajectory prediction, real-time evaluation and optimization, and drilling borehole trajectory control (Koryabkin et al., 2019). These devices assist keep the drilling path on track, maximizing efficiency and avoiding deviations.

2.5.3. Intelligent Prediction of Well Trajectory

The geological reservoir model is the basis for intelligent borehole trajectory design, which can be enhanced and automated with intelligent technologies such as computer vision algorithms. The intelligent design technique considers torque, resistance, and overall length to increase the reservoir's contact area while remaining within curvature restrictions. In comparison to the traditional design model, the time cost is lower. Well trajectory design is a parameter matrix optimization issue with common objectives such as borehole length, string torque, target hit, and oil and gas output (Tunkiel et al., 2021).

2.5.4. Real-time Evaluation and Optimization of Wellbore Trajectory

Intelligent algorithms can be applied in real-time to assess the discrepancy between the actual drilling trajectory and the designed trajectory. By adjusting controllable parameters such as drilling angle, these algorithms can close the gap and bring the wellbore back on course. Drilling trajectory optimization is a multi-objective technique that focuses on key metrics such as minimizing deviation, reducing well length, and optimizing friction, while also managing constraints such as the deflection capabilities of the bottom-hole assembly (BHA) (Halafawi and Avram, 2019). Unlike well trajectory design, which typically focuses on initial planning, trajectory optimization requires real-time calculation of outcomes, demanding higher processing efficiency (Li et al., 2018). When evaluating trajectory, it is crucial to consider not only the degree of alignment between the actual and desired trajectory but also factors such as cost, risk, and the drilling stability of the wellbore.

2.5.5. Drilling Well Trajectory Control

Qualified specialists must make a variety of decisions during the geosteering and rotational steering building procedures, and manual judgment is prone to error. Artificial intelligence technology allows for total automation of drilling well trajectory guidance and control, including measurement, downhole information transfer, and control instruction generation and execution (Figure 5).

Figure 5 Intelligent Prediction and Optimization of Well Trajectory

2.5.6. Intelligent Warning and Control of Drilling Risk

Drilling problems such overflow, loss, halted drilling, and well collapse are primarily caused by near-well formation instability and imbalances in the wellbore-formation interaction (Hou et al. 2020). To avoid these concerns, better prediction and real-time diagnostics are required. However, difficult formation characteristics, such as microfractures, high bottom-hole temperatures and pressures, and the danger of kicks and blowouts, make it difficult to accurately forecast and diagnose drilling accidents (Alkinani et al., 2020).

Intelligent risk prediction for difficulties such as overflow, halted drilling, and well collapse is difficult due to the numerous contributing elements. To solve this, artificial neural networks, random forests, support vector machines, and case-based reasoning are commonly used to anticipate, minimize, and correct losses. Lost circulation prediction, for example, considers loss pathways, loss pressure, and loss rates (Crisci et al., 2012). The analysis encompasses a wide range of geological and engineering features, with an emphasis on precision and timeliness. However, due to the dispersion of loss-related data, gathering, screening, and integrating this information remains difficult. Furthermore, the challenges of insufficient data and limited data types in the algorithm model's training set have become more apparent, resulting in a lack of on-site validation and optimization. It is critical to improve the accuracy and reliability of lost circulation prevention and plugging algorithm models, speed up the development of expert systems, and assure the digital and intelligent transformation of circulation prevention and plugging technology (Santos and Taleghani, 2021).

Artificial intelligence systems can effectively describe the correlations between different variables and drilling risks, as well as predict logging data noise. In contrast, sophisticated algorithms, which are more sensitive to data variations, can detect threats faster. Relevant research includes risk prediction before drilling, risk warnings and diagnostics, and risk grade assessment (Yin et al., 2017). The current work focuses on early detection and diagnosis of drilling process problems, as well as risk prediction and grade assessment (Figures 6-8).

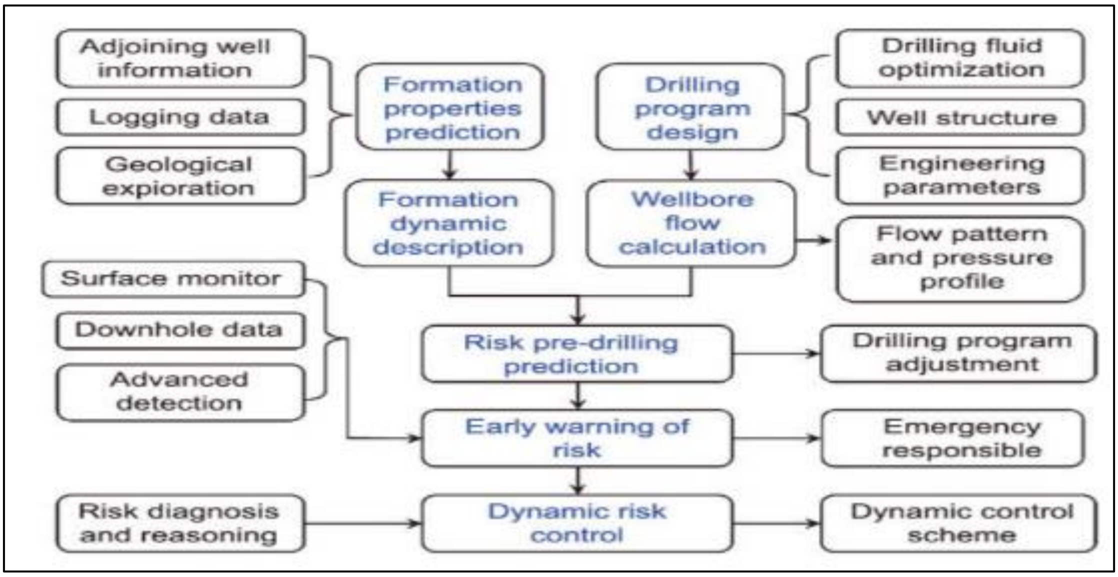

Figure 6 Application Scenarios for AI in Drilling Risk Control

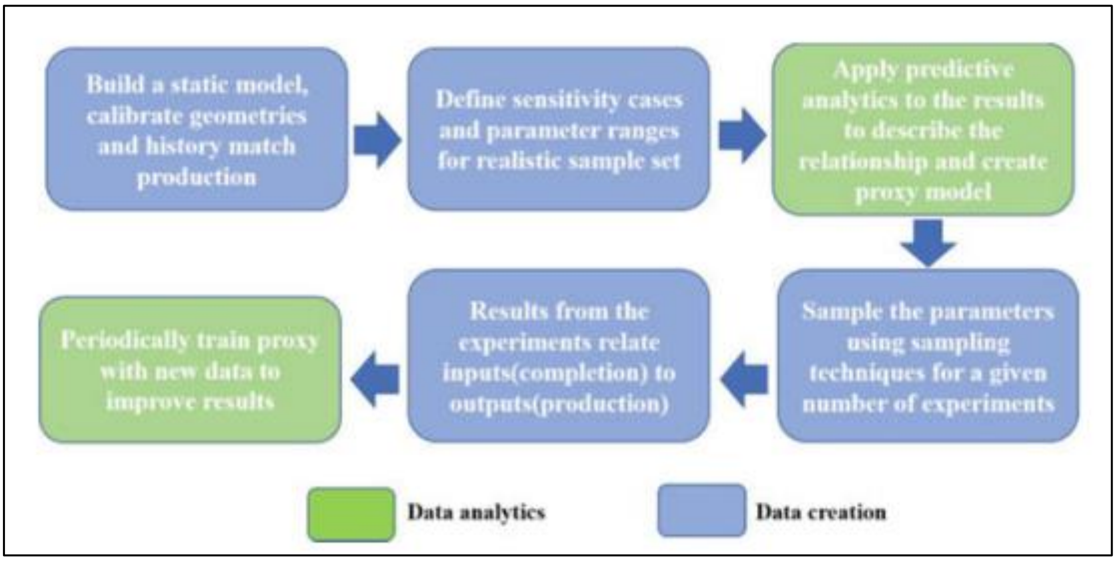

Figure 7 Generic workflow to build a predictive proxy model for completion optimization

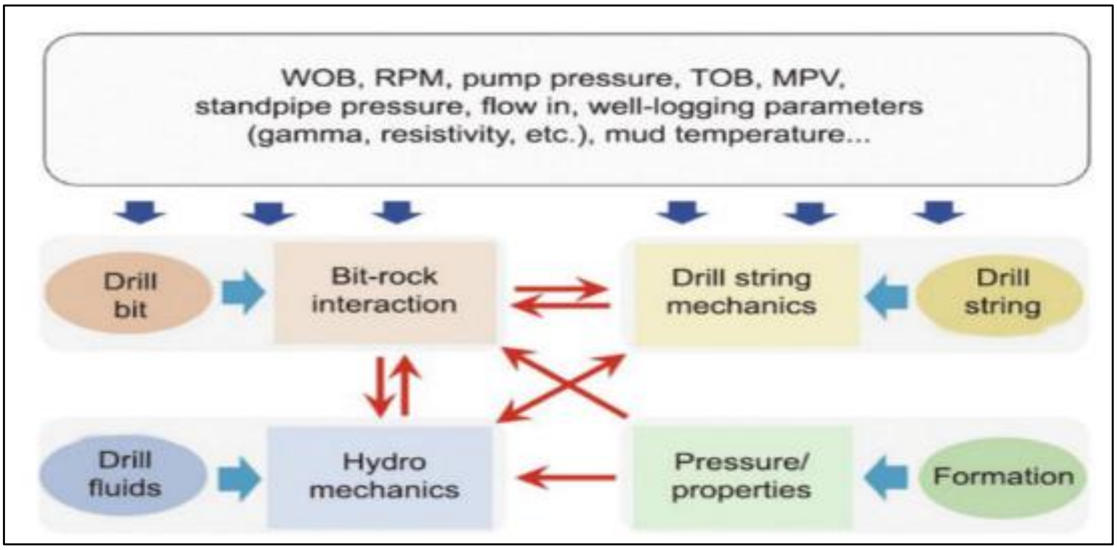

Figure 8 Generic Workflow to build a predictive proxy model for completion optimization (Yin et al., 2022)

2.5.7. Intelligent Evaluation and Optimization of Cementing Quality

Cement quality is directly tied to the proper operation of oil wells. As a result, assessing cementing quality has become an important part of petroleum logging interpretation (Tran et al., 2020). In parallel, intelligent interpretation of logging data, aided by new information processing technologies, has arisen as an important area of research and development. This strategy increases the intelligence of logging interpretation while also boosting its correctness and dependability. The acoustic amplitude logging method is one of the most commonly utilized intelligent approaches for assessing cement quality. This approach assesses cement quality by measuring the amplitude of the first wave in the formation echo.

A machine learning approach can be utilized to develop a pre-job cementing quality prediction model that takes advantage of the abundance of previous well data. This methodology can overcome the constraints of human experience, which frequently leads to blind spots in establishing quality predictions, resulting in improved forecasting accuracy. Furthermore, the cementing design and construction scheme can be modified before usage, increasing construction efficiency and offering greater direction for field operations. Furthermore, the work mode shifts from one that relies on expert knowledge and has a limited study scope to a more automated system that collects data, analyzes it, generates models, and predicts results.

2.5.8. Intelligent Completion Design and Optimization

Intelligent well completion typically entails downhole automation, remote sensing, and a control system. It represents a more modern and efficient technique to oil production and recovery (Klie, 2015). Intelligent well completion technology enables the installation of a permanent monitoring system within the well, allowing for simultaneous multi-layer extraction as well as precision mining on a single layer. This system captures, transmits, and analyzes borehole production data while also monitoring reservoir and production performance remotely. These advances in smart completion technology will dramatically lower costs and improve the dependability of existing systems, hastening the development and implementation of intelligent well finishing techniques.

2.5.9. Overall Optimization and Intelligent Decision-making

Drilling and completion systems are intrinsically complex, with several interrelated downhole subsystems including geosteering, rock breaking, hydraulics, and drillstring systems. The basic purpose of drilling is to build efficient wells while reducing risks and expenses. As a result, drilling optimization has various objectives and subsystems, necessitating the creation of an integrated model. A important use of artificial intelligence in drilling and completion is to optimize the entire drilling process and enable intelligent decision-making (Cayeux et al., 2021). This strategy will improve drilling safety, shorten drilling cycles, and minimize expenses. To attain these objectives, it is critical to combine physics-based and data-driven techniques, examine the coupling mechanisms across subsystems, and develop mathematical models for the integrated subsystems. The integrated model should be dynamic and serve as the foundation for drilling optimization, taking into account both controllable surface operational elements and drilling risks. Operating parameters should be designed to avoid unwanted phenomena like column lifting or pipe sticking.

Multi-objective optimization algorithms and intelligent decision-making processes must be well-defined, with goals such as increased drilling rates and cost efficiency. To meet real-time operational requirements, these algorithms must be quick and efficient.

Finally, a framework should be created to integrate these models and algorithms, enabling overall optimization and intelligent decision-making throughout the drilling process. To achieve the best results with intelligent or autonomous drilling, all drilling components must be smoothly linked. Although extensive research has been conducted in areas such as model construction, framework design, and system development (Reolon et al., 2020), efforts to optimize the drilling process and make intelligent decisions are still in their early stages.

2.6. Challenges to Adoption of Digital Technology and Sustainability in Oil and Gas Well Construction Delivery

The use of digital technology in the oil and gas sector has transformative potential, particularly in terms of improving the sustainability of well building deliveries. Artificial intelligence (AI), digital twins, and advanced analytics are examples of technologies that can help with process optimization, safety, and environmental impact reduction. However, the transition to digital solutions presents significant obstacles that must be carefully considered. These issues, which include high implementation costs, regulatory uncertainty, and the need to upskill the workforce, pose substantial barriers to the widespread use of digital technology in the sector.

3. High Cost of Implementation

3.1. Financial Investment in Digital Technologies

The oil and gas industry is capital-intensive, with financial investments reviewed thoroughly. Implementing digital technology incurs large upfront expenses for hardware, software, and licenses. Digital twins, for example, require high-performance computing infrastructure, strong data integration systems, and continuous updates (Mariani et al., 2021). Smaller businesses frequently find these costs prohibitive, particularly in light of volatile oil prices. This unpredictability may result in budgetary constraints, making it harder to provide funds for long-term digital transformation initiatives (Jones et al., 2022). Furthermore, the cost of unique solutions customized to individual operating demands may surpass early projections, discouraging investment.

1.2 Recurring Costs and Maintenance

Beyond the initial implementation, digital technologies require ongoing financial commitments. These include costs for software upgrades, cybersecurity measures, and the integration of new features to keep systems relevant. For instance, predictive maintenance systems powered by AI must be regularly updated with new algorithms and datasets to maintain their effectiveness (Brown *et al.*, 2022). Such recurring costs can strain the budgets of companies already grappling with thin profit margins.

3.2. Opportunity Costs

The opportunity costs associated with digital adoption also contribute to the challenge. Transitioning to digital systems often involves downtime during installation and integration phases. In the high-stakes environment of oil well construction, any operational disruption can lead to significant revenue losses.

3.3. Addressing Financial Barriers

To address these financial challenges, collaborative funding models and industry-wide partnerships can be explored. Governments and industry associations could play a pivotal role in offering subsidies, tax incentives, or grants for digital transformation projects. For example, the Norwegian government's subsidies for digitalization in the energy sector have been instrumental in accelerating technology adoption (Peterson *et al.,* 2023

4. Regulatory Uncertainties

4.1. Fragmented Regulatory Landscape

The worldwide oil and gas business operates under a variety of regulatory frameworks, with considerable differences between countries and regions. This fragmentation affects the use of digital technologies because businesses must traverse many compliance standards. For example, the use of AI and big data analytics creates concerns regarding data privacy and ownership, particularly in countries with strict data protection rules, such as the European Union's General Data Protection Regulation (GDPR).

4.2. Environmental Regulations

As sustainability becomes a focal point, aligning digital innovations with environmental regulations is crucial. However, a lack of clear guidelines on how digital tools can be leveraged to meet emission reduction targets often leaves companies hesitant to invest. For example, real-time monitoring systems that measure emissions during drilling operations may require validation by regulatory bodies before their results are deemed credible (Adams *et al.,* 2021).

4.3. Cybersecurity and Data Sovereignty

Digital technologies increase exposure to cybersecurity risks, prompting concerns from both regulators and industry stakeholders. The protection of sensitive data, including proprietary drilling methods and geological information, is paramount. Regulatory bodies often impose strict requirements for data storage, encryption, and access control, which can add complexity and cost to digital transformation efforts (Brown *et al.,* 2022).

4.4. Addressing Regulatory Challenges

To mitigate regulatory uncertainties, a collaborative approach is essential. Governments, industry leaders, and technology providers must work together to develop standardized guidelines that foster innovation while ensuring compliance. Initiatives such as the Open Subsurface Data Universe (OSDU) platform, which promotes data standardization in the energy sector, exemplify the benefits of such collaboration (Peterson *et al.,* 2023).

5. Need to Upskill the Workforce

5.1. Skills Gap in the Workforce

Digital technologies require a workforce proficient in data science, machine learning, and digital system management. However, the traditional skill sets prevalent in the oil and gas industry often lack alignment with these requirements. For example, drilling engineers may excel in mechanical processes but lack expertise in managing AI-powered systems or interpreting advanced analytics (Adams *et al.,* 2021).

5.2. Resistance to Change

Cultural resistance within organizations further complicates workforce transformation. Employees accustomed to conventional practices may be reluctant to adopt new technologies, fearing obsolescence or increased workloads. This resistance can slow down digital adoption and undermine its potential benefits (Brown *et al.,* 2022).

5.3. Training and Development

Addressing the skills gap requires targeted training and development programs. Collaborations with academic institutions and technology providers can facilitate the creation of curricula tailored to the industry’s needs. For instance, partnerships between oil companies and universities have successfully introduced courses on digital drilling technologies, enhancing workforce readiness (Jones *et al.,* 2022).

5.4. Recruitment of Digital Talent

In addition to upskilling existing employees, the industry must attract fresh talent with digital expertise. However, competition from tech-centric sectors such as IT and finance poses a challenge. Offering competitive compensation, flexible working conditions, and opportunities for professional growth can help attract and retain digital talent.

5.5. Addressing Workforce Challenges

To overcome workforce-related barriers, companies should adopt a phased approach to digital transformation. Piloting technologies on a smaller scale allows employees to adapt incrementally while demonstrating tangible benefits. Moreover, fostering a culture of continuous learning and innovation can encourage acceptance and engagement with digital initiatives (Peterson *et al*., 2023).

6. Conclusion

The adoption of digital technologies presents a transformative opportunity for enhancing the sustainability of oil and gas well construction delivery. Through the integration of advanced tools such as artificial intelligence, digital twins, and IoT, the industry can achieve significant improvements in efficiency, safety, and environmental stewardship. These technologies enable precise resource management, real-time monitoring, and predictive analytics, which collectively reduce operational waste, and promote more sustainable practices. However, the transition to digitalization is not without challenges. High implementation costs, workforce skill gaps, cybersecurity risks, and regulatory uncertainties remain critical barriers. Addressing these challenges requires a concerted effort from industry stakeholders to invest in training programs, foster collaboration among operators, technology providers, and regulators, and establish robust digital infrastructure. This review underscores that digital transformation is a key enabler of sustainability in well construction delivery. As the oil and gas sector faces increasing pressure to balance economic performance with environmental responsibility, the adoption of digital technologies offers a viable pathway to achieving these dual objectives. Future research and development should focus on scalable, cost-effective solutions that further align digital innovation with the industry's long-term sustainability goals. By doing so, the oil and gas sector can secure its relevance in a rapidly evolving energy landscape while contributing to global sustainability efforts.

Based on the findings of this review, the following recommendations are proposed to accelerate digital technology adoption and enhance sustainability in oil and gas well construction delivery:

- **Investment in Digital Infrastructure**: Oil and gas companies should prioritize investments in robust digital infrastructure, including high-speed data networks, cloud computing, and edge computing systems, to support seamless integration of digital technologies in well construction operations.
- **Skill Development and Workforce Training**: Comprehensive training programs are essential to upskill the workforce in digital tools such as artificial intelligence, machine learning, and advanced analytics. Collaboration with academic institutions and technology providers can facilitate the development of specialized training curricula.
- **Regulatory Framework Alignment**: Governments and regulatory bodies should establish clear policies and standards that encourage the adoption of digital technologies while ensuring environmental compliance and data security. Incentives such as tax breaks or subsidies for digital transformation initiatives could further drive adoption.
- **Collaboration and Knowledge Sharing**: Enhanced collaboration among industry stakeholders—including operators, technology providers, and research institutions—can foster innovation and the development of tailored digital solutions. Sharing best practices and case studies can also help overcome implementation barriers.
- **Sustainability Integration**: Companies should align digital adoption strategies with their sustainability goals. Digital tools should be leveraged to monitor environmental impacts, optimize resource usage, and reduce greenhouse gas emissions throughout the well construction lifecycle.
- **Pilot Projects and Scalability**: Implementing pilot projects to test and refine digital technologies in controlled environments can provide valuable insights into their effectiveness and scalability. Successful pilot initiatives can then serve as benchmarks for broader industry adoption.
- **Cybersecurity Measures**: As digitalization increases reliance on interconnected systems, robust cybersecurity frameworks must be established to protect sensitive data and ensure the resilience of critical operations against cyber threats.

Compliance with ethical standards

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The authors declare that there is no conflict of interest.

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