The Application of Digital Twin Technology Integrated with AI in Intelligent Oilfield Production

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Abstract:Based on actual engineering practices in oilfields, this paper systematically presents the architecture and operational mechanisms of integrating digital twin and AI technologies. Focusing on three core application scenarios—optimization of oil production schemes, predictive maintenance of oilfield equipment, and intelligent energy scheduling across the entire field—the paper deeply analyzes technical implementation pathways, methods, practical outcomes, and application advantages through real-world projects at Changqing, Shengli, and Daqing oilfields. Practical experience demonstrates that the integration of digital twin and AI technologies effectively addresses longstanding challenges in traditional oilfield operations, significantly enhancing precision management, reducing operational costs, minimizing equipment failure downtime, and optimizing energy consumption structures. This technology provides solid technical support for the digital transformation and intelligent upgrading of oilfields, improving quality and efficiency while enabling green and low-carbon production. It exhibits strong engineering practicality, implementability, and broad industry promotion value, offering reliable reference for intelligent retrofitting projects in similar oil and gas fields.
Key words:Digital twin; AI technology; smart oilfield; production optimization; equipment operation and maintenance; energy dispatching

1 INTRODUCTION

Under the dual strategic guidance of "Digital China" and "Smart Energy," traditional energy production models—characterized by high energy consumption, reliance on experience, and extensive operations—are undergoing fundamental transformation. As a core pillar of national energy security, the oil and gas industry has made digitalization and intelligent transformation an inevitable path toward high-quality development. With increasing years of field exploitation, most major domestic oilfields have gradually entered the mid-to-late stages of development, facing numerous operational challenges such as declining formation pressure, rising water cut, reduced single-well productivity, severe equipment aging, soaring maintenance costs, and persistently high energy consumption. The shortcomings and drawbacks of conventional management models are becoming increasingly evident.

Leveraging next-generation information technologies—including the Internet of Things (IoT), big data, 5G communication, digital twins, and artificial intelligence (AI)—to build smart oilfields is now the key technical pathway to address these challenges in mature fields. By establishing end-to-end data connectivity across geological exploration, drilling, oil production, gathering and transportation, equipment operation and maintenance, energy management, and safety control, a new production system driven by data, empowered by intelligence, and enabled by precise control can be established. In recent years, major domestic oil and gas fields have initiated intelligent upgrading and transformation programs. Digital twin and AI integration technology, serving as the core enabler for smart oilfield development, is progressively replacing traditional manual and experiential management approaches. Thanks to its advantages in virtual-physical integration, simulation-based forecasting, intelligent decision-making, and proactive prediction, this technology plays an irreplaceable role in optimizing oilfield operations and enabling fine-grained control.

For a long time, most domestic oilfield operations, equipment management, and energy dispatching have heavily relied on the on-site practical experience of frontline technicians and managers, resulting in a management model marked by strong dependence on experience, delayed responses, and coarse operations. During oil production, dynamic changes in reservoir parameters, real-time fluctuations in well conditions, and evolving block development scenarios make it difficult for human operators to accurately detect subtle changes. Adjustments to production parameters and optimization of production regimes often require multiple rounds of field trials and repeated tuning, leading to prolonged adjustment cycles, substantial consumption of labor, electricity, and materials, and frequent risks of unstable well performance, increased water content, and reservoir damage due to poorly adapted strategies—all of which negatively impact overall field development efficiency. In equipment management, traditional fixed-interval maintenance schedules lack flexibility, while reactive emergency repairs are inherently delayed and unable to identify hidden faults or aging trends, making sudden equipment failures and production interruptions highly likely. In energy management, manual scheduling suffers from slow response times and rigid allocation, failing to adapt to dynamic production loads, thus causing persistent issues of energy

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waste and overconsumption. These problems severely hinder the efficient, refined, and sustainable development of modern oilfields, necessitating a comprehensive transformation of management practices through intelligent technologies.

Digital twin technology enables the precise creation of a virtual mirror of physical oilfield production environments, achieving real-time data synchronization and operational coordination between physical assets and their digital counterparts. When combined with AI-powered analytics, simulation, forecasting, and autonomous optimization capabilities, this integrated approach breaks through the technological bottlenecks of traditional management, enabling proactive prediction, real-time control, and post-operation review throughout the entire production lifecycle. Compared to conventional experience-based management, this fusion technology offers significant advantages including full-spectrum data integration, high simulation accuracy, intelligent decision-making, and strong implementation capability, effectively addressing various fine-grained management challenges in oilfield operations. Drawing on years of hands-on experience in oilfield engineering operations and technical management, this paper systematically outlines the core theoretical framework of digital twin and AI integration technologies. Focusing on practical implementation cases from major domestic oilfields, it conducts an in-depth analysis of the application pathways, outcomes, and optimization value of these technologies across three key scenarios: oil production, equipment operation and maintenance, and energy dispatching. The paper summarizes existing challenges and improvement directions in field applications, providing replicable and actionable engineering references for digital transformation, technology deployment, and enhanced operational efficiency in similar intelligent oilfields.[1,2]

2. Core Principles of Digital Twin and AI Integration

2.1 Core Architecture of Digital Twin Technology

Digital twin technology is a full lifecycle system that leverages core technologies such as IoT sensing, high-precision 3D modeling, 5G data transmission, virtual simulation, and edge computing to create a 1:1, high-fidelity digital replica of all physical assets in an oilfield—such as oil wells, pumping units, gathering and transportation equipment, pipeline networks, wastewater treatment stations, and production facilities. Its key technical advantage lies in establishing a four-dimensional closed-loop integration among physical entities, virtual models, real-time data, and business applications, effectively overcoming the traditional problems of isolated data, disconnected scenarios, and fragmented management in oilfield operations. By deploying numerous high-precision IoT devices—including pressure sensors, flow meters, temperature transmitters, vibration acquisition terminals, and video surveillance systems—on-site, the system continuously collects comprehensive operational data 24/7, including bottomhole pressure, wellhead flow rate, casing temperature, equipment rotational speed, vibration amplitude, pipeline pressure loss, and ambient temperature and humidity. Through 5G and industrial internet connectivity, this data is transmitted with low latency and synchronized in real time to cloud-based virtual models. Utilizing advanced 3D modeling techniques, the system reconstructs realistic scenes of terrain, equipment structures, pipeline layouts, and well pad distributions, enabling millisecond-level replication of actual field conditions. This allows for full-process visualization, dynamic simulation, historical state tracing, and scenario-driven inference, providing a precise, comprehensive, and real-time data foundation for subsequent AI-powered intelligent analysis and decision optimization.

2.2 The Enabling Role of AI Technology

A standalone digital twin model can only replicate physical conditions, visualize data, and trace production status—it represents a "passive perception" approach, lacking the capability for autonomous analysis of operational patterns, risk prediction, or production optimization. It cannot meet the demands of modern smart oilfields for autonomous decision-making, precise control, and proactive forecasting. Deep integration of AI algorithms fully addresses these limitations, enabling a complete upgrade across the entire workflow from "perception - analysis - prediction - decision - optimization." During implementation, machine learning, deep learning, big data clustering, and multi-objective optimization algorithms are applied to analyze vast volumes of accumulated historical production data, real-time operational data, equipment maintenance records, and energy consumption metrics stored on the digital twin platform. These methods accurately identify oil production patterns under different reservoir blocks and operating conditions, uncover hidden features of equipment failures, detect correlations in energy consumption fluctuations, and track trends in subsurface parameters. Furthermore, through algorithmic iterative simulation, multi-scenario comparison, and intelligent parameter fitting, the system enables trend forecasting and global optimization for critical business scenarios such as production regimes, equipment operation states, energy distribution strategies, and maintenance scheduling. This fundamentally transforms traditional oilfield management practices—reliant on experience, reactive control, and trial-and-error approaches—into a proactive, intelligent decision-making framework. As such, it serves as the core technological pillar driving the digital transformation of smart oilfields.[3,4]

3. Digital Twin and AI Technology in Specific Engineering Applications for Smart Oilfields

3.1 Intelligent Optimization of Oil Production Schemes

Oil production is the core operation in oilfield management, and the scientific accuracy of production regimes, operational parameters, and water injection plans directly determines individual well productivity, reservoir recovery efficiency, and overall field development performance. Domestic oilfields feature complex and diverse geological conditions, with low-permeability fields, fault-block fields, mature fields, and high-water-cut fields coexisting. Significant variations exist across different blocks, formations, and wells in terms of formation permeability, porosity, reservoir pressure, and oil saturation, resulting in highly individualized characteristics. Traditionally, production planning and parameter optimization rely heavily on technicians' accumulated field experience combined with static geological data to establish fixed production schemes. These methods fail to adapt to dynamic changes in reservoir conditions, leading to poor generalizability, weak specificity, and low precision in manually designed production plans. To achieve optimal extraction conditions, multiple trial-and-error tests are often required at the site, repeatedly adjusting key parameters such as pumping unit stroke length, speed, production quotas, water injection intensity, and injection cycles—resulting in extremely high trial costs. Frequent on-site adjustments also disrupt stable production conditions, causing fluctuations in reservoir pressure, rising crude oil water content, and unstable production capacity. This not only wastes substantial amounts of electricity, water, labor, and resources but also shortens the period of stable production, severely impacting the economic returns of oilfield development.

By leveraging digital twin technology, a high-precision virtual model of the entire oilfield block can be established, enabling 1:1 replication of geological structures, wellpad layouts, equipment status, pipeline networks, and production conditions. This integrates comprehensive multidimensional data—including geological survey information, single-well formation parameters, historical production data spanning over five years, water flooding development records, operational logs, and maintenance data—into a complete digital foundation for oilfield operations. On this basis, an intelligent simulation and optimization system is built by embedding AI-based multi-objective genetic algorithms, operating condition fitting algorithms, and parameter iteration algorithms. Engineers no longer need to conduct on-site trials; instead, they can customize various combinations of production parameters within the virtual twin platform, simulating oilfield production under different production rhythms, water injection patterns, and allocation schemes. The system rapidly evaluates corresponding output metrics, including production rates, water cut trends, reservoir pressure changes, energy consumption levels, and extraction stability. The AI algorithm autonomously performs comparative analysis, iterative screening, and parameter fitting across thousands of operational scenarios, accurately identifying optimal parameter sets tailored to individual well characteristics. It automatically selects production plans that balance stable output, increased production, energy efficiency, and long-term sustainability, precisely aligning with reservoir oil production dynamics and energy evolution trends.

This intelligent simulation and optimization approach completely transforms the outdated practice of repetitive on-site trial-and-error and experience-based tuning. Without conducting blind physical experiments, multiple production schemes can be quickly iterated, compared, filtered, and optimized through virtual simulation, significantly reducing the debugging cycle. It effectively avoids waste of crude oil resources, power, labor, and materials, stabilizes oilfield output, and substantially improves both single-well production efficiency and overall reservoir recovery rates. The technology is highly adaptable to various complex scenarios, including low-permeability wells, enhanced recovery in mature fields, high-water-cut well treatments, and development of complex fault-block reservoirs, demonstrating strong scenario compatibility and practical engineering value.[6]

Specific engineering application case: Optimization of oil production scheme in a low-permeability reservoir block at Changqing Oilfield

A major development block in Changqing Oilfield is located in the Ordos Basin and represents a typical "triple-low" reservoir characterized by low permeability, low porosity, and low abundance. The reservoir exhibits extreme heterogeneity, poor formation connectivity, rapid pressure decline, and high difficulty in both production and stable output, making it a representative example of complex and inefficient oilfields in China. Under traditional development models, production plans for this block were entirely based on engineers' experience, with core parameters such as pumping unit stroke rate, stroke length, allocated production quotas, and water injection intensity set uniformly without considering individual well differences. This lack of personalized optimization led to insufficient capacity utilization in many wells and a high proportion of low-yield, inefficient wells. To improve single-well productivity, field staff long relied on manual, repeated adjustments of production parameters, with each adjustment cycle lasting 7 to 15 days per well. During these periods, equipment was frequently started and stopped, and parameters changed often, consuming substantial labor and electricity resources while also easily causing operational instability, increased water cut, and imbalance in reservoir energy—further exacerbating inefficiencies. As a result, the overall recovery rate of the block has remained consistently below the industry average, severely limiting improvements in oilfield development efficiency.

To fully address the issues of inefficient development, high trial-and-error costs, and unstable production capacity in this reservoir block, a digital twin combined with an AI-based intelligent oil production optimization system was fully implemented in 2023. A high-precision digital twin virtual model covering all 236 producing wells was established, incorporating detailed geological parameters for each well—including formation permeability, porosity, original formation pressure, oil saturation, and reservoir thickness. The system integrated five years of production data, monthly water injection records, operational fluctuations, equipment operation logs, and maintenance history to build a dedicated large-scale database for reservoir production.

Leveraging this database, an AI multi-objective genetic optimization algorithm was deployed to create a simulation and forecasting model tailored for low-permeability reservoirs, which are characterized by rapid pressure decline, production sensitivity, and quick water cut increase. Engineers used the virtual platform to conduct multidimensional and multi-group simulation tests on 12 key production parameters—such as pumping unit stroke rate, stroke length, daily allocated production, water injection intensity, injection cycle, and shut-in time—completing over 1,200 sets of parameter combinations for comparative simulation. This enabled comprehensive analysis of how different parameter settings affect production, water cut, formation pressure, and energy consumption. Through deep learning of simulation data, the AI algorithm automatically iteratively optimized parameter combinations, identifying personalized optimal production regimes suited to the unique geological characteristics of each individual well, precisely aligning with reservoir oil production patterns and pressure trends.

After field implementation, the adjustment cycle for single-well production plans was reduced to just 1 - 2 days, eliminating blind on-site trial-and-error operations entirely. The block's average water cut decreased by 3.2%, average daily oil production per well increased by 8.6%, and overall recovery efficiency improved by 1.8 percentage points. Annual savings in electricity, labor, materials, and other production costs exceeded 1.2 million yuan. These significant improvements in quality and efficiency clearly demonstrate the substantial application value of this technology in complex oilfield development.[7–9]

3.2 Intelligent Predictive Maintenance for Oilfield Equipment

Core production equipment in oilfields—including oil well pumps, oil transfer pumps, compressors, gathering and transportation pipelines, and water injection systems—serves as the foundation for continuous and stable operations. The operational condition of this equipment directly determines the oilfield's production capacity and safety. These devices typically operate 24/7 under fluctuating loads, compounded by harsh outdoor environments involving wind, sand, humidity, temperature variations, and corrosion. As a result, frequent issues such as wear, aging, fouling, and corrosion arise, leading to diverse failure types with complex root causes. For years, domestic oilfield equipment management has relied on a traditional model combining "scheduled maintenance" and "emergency repairs," which is coarse-grained and lacks precision.

Scheduled maintenance follows uniform cycles and standards without considering differences in equipment operating conditions, service life, or load intensity. This leads to unnecessary disassembly and servicing of otherwise healthy equipment, resulting in significant waste of labor, materials, and time. Meanwhile, latent faults such as bearing wear, motor degradation, minor pipeline blockages, and seal failures often go undetected until they cause sudden equipment shutdowns. Such incidents disrupt crude oil production and transportation, causing substantial output losses and posing serious safety risks including equipment burnout, pipeline leaks, and environmental compliance violations.

By leveraging digital twin technology, a 1:1 three-dimensional, high-fidelity model can be created for all core production equipment, establishing a virtual electronic ledger covering the entire equipment lifecycle. Comprehensive data—including factory specifications, installation and commissioning records, operational years, maintenance logs, fault history, and spare parts replacement details—are fully integrated, enabling digital, visual, and traceable equipment management. High-precision sensors—such as vibration, temperature, current-voltage acquisition terminals, and pressure modules—are installed at critical locations including pump bearings, motors, pump chambers, compressor inlets and outlets, and key pipeline nodes. These continuously collect dynamic operational data (e.g., vibration amplitude, housing temperature, working current, rotational speed, inlet/outlet pressure) around the clock, transmitting it via 5G networks to a cloud-based digital twin platform. This ensures millisecond-level synchronization between physical equipment status and its virtual model.

Combined with AI-based fault feature recognition algorithms and trend prediction models, real-time data is compared against historical normal operation data and known fault samples. This enables precise detection of subtle operational anomalies, effectively identifying hidden faults and aging trends that are difficult to spot during manual inspections. Potential risks such as bearing wear, motor overheating, pipeline clogging, seal deterioration, and abnormal current draw can thus be predicted in advance.

Based on AI analysis results, the system automatically generates optimized, tiered maintenance plans, accurately pinpointing fault locations, forecasting failure timing and severity, and distinguishing between routine maintenance, focused inspections, and emergency repairs. This marks a fundamental shift from reactive and scheduled maintenance to intelligent, predictive, and precise maintenance. On one hand, it proactively identifies latent faults, preventing unexpected outages such as pump failures, pipeline blockages, and transfer pump breakdowns, thereby avoiding production interruptions and ensuring continuous, stable operations. On the other hand, it eliminates ineffective, redundant, and excessive maintenance activities, significantly reducing material and labor costs, slowing equipment aging, extending the lifespan of core assets, and decreasing replacement frequency. Ultimately, it provides strong support for fine-grained, lifecycle-wide equipment management in oilfields.[10,11]

Specific engineering application case: Intelligent equipment operation and maintenance practice at a certain oil production plant in Shengli Oilfield

A coastal oil production plant in Shengli Oilfield is a key production area, currently operating over 320 producing wells and equipped with more than 460 sets of core equipment, including pumping units, oil transfer pumps, compressors, and gathering and transportation pipelines. Due to the long service life of these assets and their location in a coastal tidal flat region exposed to high humidity, high salinity, frequent sandstorms, and severe corrosion, problems such as equipment corrosion, wear, abnormal vibration, and seal failure occur frequently. The plant has long relied on traditional equipment management practices—primarily quarterly scheduled maintenance and reactive repairs after failures—which have significant drawbacks. On one hand, standardized, one-size-fits-all maintenance schedules ignore variations in equipment operating conditions and health status, leading to frequent disassembly and replacement of parts for otherwise stable and healthy equipment. This results in widespread ineffective and excessive maintenance, wasting substantial human resources, materials, and labor hours. On the other hand, latent faults cannot be predicted in advance; minor issues such as bearing wear, pipeline micro-blockages, and motor aging accumulate over time, eventually causing unexpected equipment shutdowns. According to operational records, prior to system upgrades, the plant experienced an average of over 80 unplanned equipment outages annually, each lasting 4 to 8 hours. Each incident not only required extensive manpower and consumables for repair but also directly halted crude oil production, resulting in significant annual output loss and increased pressure on safety and operational control.

To fundamentally address the challenges of inefficient operations, high rates of unexpected failures, elevated maintenance costs, and substantial production losses, the plant fully deployed a digital twin-based AI-powered intelligent equipment operation and maintenance management system in 2022. It completed 1:1 three-dimensional digital modeling for all 460+ core equipment units and established an integrated digital platform for full lifecycle equipment management. The platform consolidates data from equipment factory documentation, installation and commissioning logs, historical maintenance records, fault registers, and spare part replacement history into standardized digital archives. Additionally, the plant upgraded its equipment sensing infrastructure by installing high-precision data acquisition terminals at critical points on key equipment such as pumping units, oil transfer pumps, and compressors. These terminals continuously collect vital operational parameters—including vibration, temperature, current, speed, and pressure—and leverage 5G industrial internet to ensure low-latency data transmission, enabling real-time synchronization between virtual models and physical equipment conditions.

The system incorporates a self-trained AI algorithm for fault feature recognition, which learns from nearly ten years of normal operation data, various fault samples, and degradation trends to build a predictive fault model tailored to the complex conditions of tidal-flat oilfields. This enables precise identification of subtle anomalies and hidden fault risks. The system can predict potential failures—such as bearing wear, motor overheating, pipeline blockage, and seal aging—7 to 15 days in advance, automatically generating accurate maintenance work orders and pushing them to maintenance personnel's devices, enabling "on-demand, precision maintenance." After two years of field application, the plant has reduced unplanned equipment failures by 65%, decreased unnecessary maintenance frequency by 58%, lowered average annual maintenance costs per unit by 30%, extended equipment lifespan by 2.5 years, and saved over 300 tons of crude oil production annually due to reduced downtime. While ensuring safe and stable production, the system has achieved significant cost reduction and efficiency improvements in equipment operations and maintenance.[12-15]

3.3 Intelligent Energy Dispatch Optimization for Oilfields

Oilfield production represents a typical high-energy-consumption, high-water-use, and high-resource-demand industrial scenario. The entire process—from oil lifting and crude oil gathering to water injection, wastewater treatment, equipment operation, and site heating—requires substantial support from electricity, industrial water, thermal energy, compressed air, and other resources. Energy consumption is widespread across numerous points, spans broad operational areas, features complex energy structures, and experiences significant dynamic load fluctuations. Traditional oilfield energy management relies primarily on manual data collection, fixed allocation, and post-event accounting, lacking capabilities for real-time monitoring, intelligent analysis, and proactive forecasting. As a result, energy dispatching remains highly inefficient.

In daily operations, energy quotas for each production unit remain fixed over long periods, unable to adapt dynamically to real-time production targets, equipment loads, or changing operating conditions. This often leads to insufficient energy supply during peak production periods, forcing critical oil extraction and water injection units to operate at reduced capacity and thereby compromising crude oil output. Conversely, during low-production periods or maintenance phases, auxiliary equipment runs idle, resulting in massive waste of electricity, water, and thermal energy. Additionally, manually collected energy data is often delayed and prone to errors, making it difficult to accurately identify high-consumption nodes and inefficient energy use. Consequently, energy control in oilfields has long remained reactive, with energy consumption per unit of oil produced remaining unacceptably high, failing to meet current policy requirements and production demands for green, low-carbon, energy-efficient, and high-quality development in the oil and gas industry.

By leveraging digital twin technology, a virtual model for comprehensive energy management across the entire oilfield can be established. This model integrates consumption, supply, and loss data for various energy types—including electricity, industrial water, thermal energy, and compressed air—and links them to real-time production loads, output targets, and operational statuses of individual production units, wells, and equipment. It builds a fully integrated, time-continuous, and element-comprehensive energy data monitoring system. The model enables real-time visualization of energy flow paths, energy distribution patterns, and load fluctuation trends throughout the oilfield, achieving transparent and visible energy management.

Combined with AI-based dynamic scheduling algorithms, the system can analyze in real time the input-output ratios, equipment efficiency, and energy load characteristics of each production unit. Based on current operational conditions, it adjusts energy allocation quotas second by second, precisely matching power, water, and thermal energy to core production units that are under high load, high output, and high efficiency. Meanwhile, it automatically reduces or cuts off energy supply to idle equipment, inefficient units, and unused processes, minimizing unnecessary energy consumption and reducing transmission losses and wastage.

Furthermore, through continuous learning of historical energy consumption data, production load patterns, and seasonal variations, the AI algorithm can accurately predict peak energy demand and potential shortages under different production stages, seasons, and output requirements. This allows for the development of scientific, fine-grained energy dispatch plans in advance, enabling dynamic balancing of overall energy loads across the oilfield. By avoiding both peak overloads and low-load waste, the system effectively reduces total energy consumption, supporting smart oilfield initiatives toward energy conservation, emission reduction, and green, low-carbon development—fully aligning with national policies for sustainable transformation in the oil and gas sector.[16,17]

Specific engineering application case: Energy intelligent dispatching renovation project at a certain operation area of Daqing Oilfield

A key operational area of Daqing Oilfield is a comprehensive production zone integrating oil extraction, crude oil gathering and transportation, water injection development, wastewater treatment, and equipment operation and maintenance. The area hosts over a thousand types of production and auxiliary equipment, featuring long production chains, numerous energy consumption nodes, and high overall energy usage—making it a typical high-energy-consuming mature oilfield operation zone. For years, the area has relied on traditional manual energy dispatching methods, with rigid and fixed energy allocation schemes that fail to dynamically adjust energy supply based on monthly production plans, daily operational loads, or equipment operating conditions. During peak production periods, insufficient power and water supply to core units such as oil extraction, water injection, and gathering systems prevent equipment from running at full capacity, directly constraining crude oil output. Conversely, during low-production periods or equipment maintenance phases, numerous auxiliary devices, wastewater treatment systems, and supporting facilities operate under no load, resulting in significant energy waste. Additionally, manually collected energy data suffers from substantial delays, making it difficult to accurately identify high-consumption points and inefficiencies. As a result, the area’s energy consumption per unit of oil produced has consistently exceeded the average for the entire oilfield, creating immense pressure to reduce energy use and meet green production targets set by the oilfield.

To address challenges related to inefficient energy management, high energy consumption, and resource waste, the operation zone completed the construction of a digital twin-based AI intelligent energy scheduling system in 2023. This system established a full-field digital twin simulation model, fully integrating energy consumption data from regional power, water supply, heating, and production equipment systems. It enables real-time collection, aggregation, analysis, and visualization of energy data across all energy types, production units, and time periods. The model precisely replicates the regional energy distribution networks, electrical layouts, and energy consumption node distributions, comprehensively linking production targets, equipment load levels, and operational conditions across all units to build a dynamic energy database. Based on this foundation, an AI multi-objective optimization scheduling algorithm model was developed, focusing on core objectives including ensuring production capacity, reducing energy consumption, improving efficiency, and stabilizing load. The system leverages deep learning techniques to analyze historical energy consumption data, seasonal patterns, and correlations between production capacity and energy use. It continuously monitors overall energy consumption trends and dynamically adjusts energy allocation quotas for each production unit within seconds, prioritizing energy supply to critical production units while shutting down idle or inefficient equipment to precisely minimize unnecessary energy consumption.

Meanwhile, by integrating AI algorithms with seasonal variations, monthly production plans, and equipment maintenance schedules, the system proactively forecasts fluctuations in energy demand and formulates three-tier energy dispatch plans at the monthly, weekly, and daily levels, enabling proactive, intelligent, and fine-grained energy management. After implementation, the overall comprehensive energy consumption of the operation area decreased by 9.3%, industrial water utilization improved by 12.5%, and no-load energy losses from equipment were significantly reduced. The annual savings in various energy costs exceeded 1.8 million yuan, successfully meeting the green and energy-efficient production targets set by the oilfield and providing a proven technical model for the green and low-carbon transformation of mature oilfields.[18-20]

3.4 International Case Studies

3.4.1 BP Company – APEX Digital Twin Platform and AI-Driven Production Optimization

BP is a pioneer in digital transformation within the oil and gas industry, with its digital twin strategy centered on the APEX (Advanced Production Excellence) platform, built through over a decade of collaboration with Palantir Technologies. APEX is a real-time digital twin system that integrates data from more than 2 million sensors across BP's global oil and gas production facilities, creating a unified operational view. The platform enables real-time simulation of production system performance, allowing engineers to test adjustment scenarios in a virtual environment, predict operational outcomes, and proactively identify potential issues.

Building upon the APEX platform, BP developed an AI-enhanced tool called Optimization Genie in early 2024, which was fully deployed by September of the same year. Optimization Genie autonomously identifies and tests bottlenecks in production systems, simulates adjustment strategies, and recommends optimal configurations to engineers. The integration of AI has reduced capacity optimization analyses—previously requiring weeks of manual effort by engineers—to just a few hours.

Notable achievements include: at the Atlantis offshore facility in the U.S. Gulf of Mexico, Optimization Genie achieved approximately 2,000 additional barrels per day in production by optimizing well placement variables and prioritizing operations—all without incurring extra costs. In 2017, analysis from the APEX platform contributed an extra 30,000 barrels per day in output for BP. In exploration, BP leveraged AI to achieve nearly 97% reliability in upstream operations and a 98% accuracy rate in predicting drilling "kick" events, with plans to save $2 billion in costs by 2026.

Technical features: BP's approach reflects the evolution of digital twins from mere visualization to autonomous decision-making. Its technical architecture consists of three layers: the data layer (integrating over 2 million sensor data points), the analytics layer (using AI algorithms to detect bottlenecks and simulate adjustments), and the application layer (delivering actionable optimization recommendations). Human engineers retain final decision authority, establishing a human-AI collaborative model of "AI suggestion - human validation - closed-loop optimization."[21]

3.4.2 Shell – Deep Integration of Dynamic Digital Twins and Predictive Maintenance

Shell has adopted a technology path for digital twin applications that emphasizes dynamic simulation and predictive maintenance. At one of Norway's largest offshore gas fields, Shell has deployed a real-time dynamic digital twin system that integrates data, visualization, and dynamic modeling capabilities, enabling engineers to replicate field conditions in a virtual environment. Since its commissioning in 2007, the field has operated using two 120-kilometer multiphase gas pipelines and an underwater gas compression system. The introduction of the digital twin allows engineers to conduct "what-if" scenario analyses, benchmark models against real-time operational data, and anticipate risks before they impact production.

In equipment maintenance, Shell collaborated with Akselos to use digital twin technology for structural analysis of a 50-year-old platform in the southern North Sea, UK. This effort successfully identified critical upgrade needs, extending the platform's operational life by 20 years and avoiding substantial investment in building a new platform.

Key technological breakthrough: Shell also led the development of RTDIP (Real Time Data Ingestion Platform), an open-source platform for real-time data ingestion, which is made available to the entire industry through Linux Foundation Energy. Designed to address the "air gap" between OT (operational technology) and IT environments, RTDIP enables secure access to time-series and event data, providing a high-quality data foundation for AI analytics. Quantifiable results: The AI-driven digital twin solution developed jointly by Shell and Capgemini reduced analysis time for inefficient and optimization-targeted wells from seven hours to 1.5 hours, achieving production increases of 1 - 1.5% for onshore operations and 1 - 2% for offshore operations. Shell executives noted that combining real-time dynamic digital twins with predictive modeling enables engineers to detect anomalies and optimize equipment parameters. Going forward, the company plans to further integrate AI-powered features to automatically flag key risks and recommend corrective actions.[22]

4. Technical Application Advantages and Engineering Value

Compared to traditional oilfield production management models dominated by manual experience and characterized by extensive, inefficient practices, the integration of digital twin and AI technologies has demonstrated remarkable technical advancement and engineering practicality through multi-scenario applications in smart oilfields. Its comprehensive advantages and engineering value are prominent and can be categorized into four core dimensions. First, it enables full-spectrum cost reduction and efficiency improvement, enhancing development profitability. By replacing conventional on-site trial-and-error operations with virtual simulation and scenario analysis, it significantly reduces waste of crude oil, electricity, labor, materials, and other resources. Precise equipment maintenance lowers operational costs, while intelligent energy scheduling minimizes unnecessary energy consumption. This holistic approach substantially cuts overall production and operation expenses, stabilizes and increases oilfield output capacity and recovery rates, and significantly improves overall economic returns from oilfield development. Second, it ensures precise and controllable production, breaking free from limitations imposed by subjective experience. By establishing a real-time linkage system between physical oilfield environments and virtual models, it enables visualization, data-driven, and intelligent management across geological conditions, production operations, equipment status, and energy consumption changes. Leveraging AI-powered big data analytics, it replaces traditional human-based, subjective judgment, greatly improving the accuracy and scientific rigor of production decisions, parameter optimization, fault handling, and energy dispatching. Third, it strengthens safety foundations and ensures stable operations. Through early prediction of equipment failures, real-time alerts for abnormal operating conditions, and virtual simulation of high-risk operations, it proactively mitigates various production safety hazards such as equipment breakdowns, operational imbalances, and excessive energy loads. This effectively reduces equipment downtime, production interruptions, and safety incidents, ensuring continuous, safe, and stable oilfield operations and elevating overall safety management standards. Fourth, it supports long-term iterative enhancement and drives industrial transformation. By continuously accumulating data throughout the entire oilfield production lifecycle—including operational, maintenance, and energy consumption data—on the digital twin platform, combined with ongoing AI algorithm optimization, it refines production models and decision-making systems. This creates a replicable, optimizable, and upgradable intelligent production management model, providing sustained technological support for the digitalization, intelligence, and green transformation of oilfields, thereby promoting high-quality development in the traditional oil and gas industry. As evidenced by three field implementation cases discussed above, this integrated technology is well-suited to meet the production modernization needs of diverse domestic oilfields, delivering significant results and offering exceptional engineering scalability and promotion value.[23-25]

5. Current Issues and Optimization

Considering the current status of intelligent transformation in major domestic oilfields, although digital twin and AI integration technologies have achieved notable success in smart oilfield applications, overall implementation remains in a transitional phase characterized by pilot projects and iterative refinement. Constrained by multiple factors—including oilfield construction age, hardware infrastructure, data systems, algorithm capabilities, and talent structure—large-scale deployment and high-precision applications still face significant shortcomings and bottlenecks, limiting the full realization of technological empowerment. First, older oilfields suffer from weak foundational data and incomplete sensing systems. Many key domestic oilfields were built decades ago with limited early-stage intelligent upgrades. The sensors and data acquisition terminals deployed on-site are outdated, low-precision, and unstable. In some remote well sites and edge production areas, sensor coverage is incomplete, creating blind spots in data collection. Moreover, frequent issues such as data transmission delays, packet loss, and data distortion from aging equipment result in untimely updates to digital twin models, causing slight discrepancies between virtual model conditions and actual field operations. This directly affects the accuracy of AI-driven data analysis and intelligent decision-making. Second, data fragmentation across multiple systems creates prominent data silos. During oilfield operations, production systems, equipment management systems, energy consumption monitoring systems, safety surveillance systems, and geological databases were typically developed independently at different times and by different vendors. These systems lack standardized data formats, incompatible interfaces, and interoperability, leading to severe data fragmentation. As a result, a unified, comprehensive data ecosystem cannot be established, making it difficult to support high-precision, multi-dimensional simulation and intelligent optimization. Third, AI algorithms exhibit insufficient adaptability to complex operating conditions. Most intelligent algorithms currently used in oilfields are trained and optimized under conventional, stable production scenarios. There is inadequate training data for special or extreme situations such as sudden weather changes, abrupt formation parameter shifts, unexpected equipment failures, large-scale maintenance shutdowns, or abnormal operational fluctuations. Consequently, prediction accuracy, optimization performance, and adaptability degrade under complex conditions, indicating that algorithm robustness needs further improvement. Finally, there is a severe shortage of interdisciplinary technical talent. Digital twin and AI-based smart oilfield technologies span multiple disciplines, including petroleum engineering, reservoir development, IoT, 3D modeling, big data analytics, and artificial intelligence algorithms, demanding highly integrated expertise from professionals. Currently, frontline oilfield technicians primarily specialize in traditional oil extraction and equipment operation, lacking sufficient knowledge in digitalization, automation, and algorithmic modeling. Skilled digital professionals are scarce, and the development of cross-disciplinary teams lags behind, significantly hindering efficient system operation, deep application, and continuous iteration.[26,27]

To address the aforementioned challenges, and in line with the trends of oilfield digitalization and engineering application needs, future improvements to the technical system can be continuously advanced through four dimensions: equipment upgrades, data integration, algorithm optimization, and talent development, thereby promoting deeper implementation and widespread adoption of technologies. First, on-site sensing devices should be iteratively upgraded by fully replacing outdated and inefficient data acquisition terminals, addressing shortcomings in remote wellsite monitoring, and integrating 5G and edge computing technologies to enhance data accuracy, transmission speed, and stability, ensuring real-time and precise mapping of field conditions in digital twin models. Second, a unified oilfield data platform should be established to standardize data formats and interface specifications across all systems, breaking down data silos related to production, operations, energy consumption, geology, and equipment, enabling centralized storage, integrated sharing, and unified scheduling of data, thus providing a robust foundation for AI algorithm refinement and simulation analysis. Third, the intelligent algorithm framework should be optimized and iterated by expanding training datasets for complex geological conditions, extreme production scenarios, and sudden failures, refining model architectures to improve prediction accuracy, fault detection, and solution optimization in specialized situations, thereby broadening the range of applicable technical scenarios. [28,29]

6. CONCLUSIONS

The deep integration of digital twin and AI technologies represents a core technical pathway for the digital transformation, quality improvement, efficiency enhancement, and green development of smart oilfields in the new era. It has fundamentally broken the traditional, experience-based, extensive, and lagging production management models, effectively addressing key industry challenges such as high trial-and-error costs in oil recovery schemes, insufficient precision in production optimization, passive and delayed equipment maintenance, frequent unexpected failures, inefficient and unbalanced energy dispatching, and lack of scientific decision-making. This paper systematically reviews the core architecture, enabling mechanisms, and integration advantages of digital twin and AI technologies, and validates their application value and implementation effectiveness across three real-world projects: oil recovery optimization in low-permeability reservoirs at Changqing Oilfield, intelligent equipment maintenance at Shengli Oilfield, and smart energy scheduling at Daqing Oilfield. By constructing a high-precision virtual mirror that covers all elements, processes, and time sequences of an oilfield, and leveraging AI-powered big data analytics, simulation modeling, trend forecasting, and iterative optimization capabilities, this integrated technology enables intelligent iteration of oil production plans, precise control of equipment operations, and scientific allocation of energy resources. It comprehensively enhances oilfield production efficiency, recovery rates, safety performance, and overall economic returns, providing solid technological support for maintaining and increasing output, reducing costs, and achieving green, low-carbon transformation in mature oilfields. The technology framework is adaptable to diverse production modernization needs across various types of domestic oilfields, featuring strong practicality, broad applicability, and significant efficiency gains, thus demonstrating exceptional engineering utility and wide-scale industrial promotion potential. Against the backdrop of digitalization, intelligence, and greening transformation in the energy sector, with continuous advancements in sensing devices, data platforms, and intelligent algorithms, the convergence of digital twin and AI will achieve full coverage and deep integration in smart oilfield development, gradually realizing unmanned operation, autonomous decision-making, and fine-grained control. This will comprehensively drive high-quality development in the oil and gas industry while offering replicable, implementable practical references and technical insights for frontline petroleum engineers and technicians engaged in intelligent oilfield construction and production management.□

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