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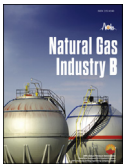

Research Article

# Intelligent safe operation and maintenance of oil and gas production systems: Connotations and key technologies

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**Abstract**

Oil and gas production systems have the characteristics of high operation and maintenance risk and great accident influence. With the deep integration of informationization and industrialization, the development direction and necessary choice of the oil and gas industry is to develop the oil and gas production system into the interconnected, multi-domain interactive cyber-physical intelligent system. In order to avoid or reduce the complex, diverse and potentially unknown safety risks in the process of oil and gas production, improve the safety and reliability of oil and gas production system and increase the production efficiency, this paper analyzes the safety problems occurring in the intelligentization process of oil and gas production system and constructs a system from the perspective of operation and maintenance based on key elements of intelligent safe operation and maintenance technology, combined with the typical production scenarios in the oil and gas production industry. And the following research results are obtained. First, the connotation of intelligent safe operation and maintenance technology is clarified, the key elements and existing problems and challenges of intelligent safe operation and maintenance technology are analyzed, and the "1-2-3-4-5-6" intelligent safe operation and maintenance technology system of oil and gas production system is constructed, which empowers six key technologies with key elements of oil and gas production to realize the essential safety of oil and gas production system. Second, the intelligent safe operation and maintenance technology actively promotes the application and implementation of condition monitoring, health management, risk assessment, intelligent early warning technologies in typical production scenarios such as drilling and extraction, storage and transportation, refining and chemical industry in up, middle and down streams of oil and gas production. Third, in view of the characteristics of oil and gas production system under digital transformation, it is proposed to develop the intelligent safe operation and maintenance technology with the functions of intelligent decision-making, active prevention and comprehensive safety in the future to help the safe construction in the field of oil and gas production and promote the safe and healthy development of the oil and gas industry. In conclusion, the research on intelligent safe operation and maintenance technology system of oil and gas production system is conducive to the safe construction in the field of oil and gas production, which will not only provide technical support for the realization of trouble-free oil and gas production system, but also provide reference for the intelligent development of the world oil and gas industry.



*Keywords:* Oil and gas production system; Safe operation and maintenance; Intelligentization; Digitization; Dynamic perception; Prevention in advance; Whole process risk control

## 1. Introduction

As a typical high-risk industry, oil and gas production is characterized by a wide variety of equipment and facilities, complex processes, and harsh working environments [1]. Although the overall safe production situation is controllable, inherent risks persist for a long time, and risk prevention capabilities in professional fields need to be continually strengthened. In recent years, the "short board effect" and "cask effect" of risk management in the process of oil and gas production have become increasingly prominent, mainly because the risk of blowout has not been thoroughly removed, refining equipment and tanks occasionally explode, and

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accidents involving fatalities in high-risk operations frequently occur [2]. Consequently, it is necessary to improve the digitization, networking, and intelligence levels of the operation and maintenance of oil and gas production systems to reduce risks, improve the safety of operation sites, and promote the digital transformation of the oil and gas industry [3].

As the core of digital transformation [4], operation and maintenance have gradually developed from the original mechanized post-operation mode driven by steam technology to the automatic regular mode driven by power technology. Currently, with the emergence of information technology, combined with the promotion of information technology and visual operation and maintenance by computer and network technology, the real-time monitoring and online evaluation of equipment operation can be achieved, enabling the timely detection and maintenance of anomalies [5]. The world is currently experiencing the fourth industrial revolution. The new generation of digital technology promotes comprehensive integration with industry, bringing about fundamental changes in production and management methods. Using information technologies such as big data, artificial intelligence, cloud computing, and digital twin, combined with physical modeling and mechanism analysis to evaluate equipment operation status, intelligent operation and maintenance enables the identification of fault modes, estimations of their severity, and predictions of remaining life. This effectively optimizes operation and maintenance decisions and allows maintenance activities to be organized in a reasonable manner [6].

Oil and gas production systems are characterized by high operation and maintenance risks, and high susceptibility to accidents. Conventional operation and maintenance methods cannot effectively perceive and handle abnormal events in a timely manner [7]. In recent years, domestic and foreign oil and gas enterprises have made significant progress in areas such as drilling safety, gathering and transportation safety [8], and remote operation and maintenance [9]. The accelerated transformation of safe production from static analysis to dynamic perception, from post-emergency response to prevention, and from single-point prevention and control to joint prevention has enhanced the safety of oil and gas production systems and achieved high-quality developments in the oil and gas industry [10]. However, there is still room for improvement in key technologies underlying the intelligent and safe operation and maintenance of oil and gas production systems. Thus, it is necessary to develop an innovative safe production technology system with desirable information, digitization, and intelligence through the integration of emerging technologies, to enhance the perception, monitoring, early warning, disposal, and evaluation capabilities of the oil and gas industry [11]. The shift from conventional techniques to intelligent and safe operation and maintenance makes it possible to cultivate and promote new models of intelligent operation and maintenance services, thereby ensuring the safe and reliable operation of production equipment [12]. In view of the current urgent demands for the digital transformation of oil and gas production, operation, and maintenance, this paper summarizes advanced technologies such as big data, digital twin, machine learning, and edge computing, define the connotation and key elements of intelligent safe operation and maintenance technology, analyze the existing problems and challenges, and construct an intelligent safe operation and maintenance technology system for the oil and gas industry. Research results provide technical support for fault-free oil and gas production, and promote the digital transformation of the conventional energy industry and the implementation of intelligent safe operation and maintenance technologies. In addition, the research results contribute to the safety of oil and gas production fields and promote the safe and healthy development of the oil and gas industry.

## 2. Connotation of intelligent safe operation and maintenance technology for oil and gas production

### *2.1. Definition of intelligent safe operation and maintenance for oil and gas production*

Intelligent operation and maintenance refers to the use of new-generation information and communication technologies (e.g., cloud computing, big data, the internet-of-things, and artificial intelligence) to achieve dynamic self-decision-making in oil and gas production systems. Intelligent and safe operation and maintenance in oil and gas production systems cover the entire process of oil and gas drilling, transportation, storage, refining, and chemical engineering, including health management, risk assessment, visual management, intelligent warning, risk prediction, and other operation and maintenance operations [13,14], as shown in Fig. 1. First, it is necessary to use edge-perception technology to acquire on-site production data, and then realize information modeling, data governance, and multi-source heterogeneous data integration based on big data technology. The aim is to fully utilize the value of data through functional algorithms and intelligent application models, enabling analysis of the intrinsic nature of monitoring data. Finally, combined with operation and maintenance service modules, this will achieve the operation and maintenance of the entire process, elements, and lifecycle of the oil and gas production system. Considering data management as the key, algorithms as the foundation, and operation and maintenance service as the platform, the deep integration of digital technology and traditional oil and gas production technology then makes it possible to continuously improve the level of digitization, networking, and intelligence of oil and gas production systems, and realize a digital transformation from conventional operation and maintenance to intelligent safe operation and maintenance.

### *2.2. Key elements of intelligent safe operation and maintenance of oil and gas production*

Oil and gas production systems have inherent risks. Existing risk prevention capabilities in different professional fields and key links still need to be strengthened [15]. Thus, intelligent safe operation and maintenance should start from three key elements: equipment safety, job safety, and process safety.

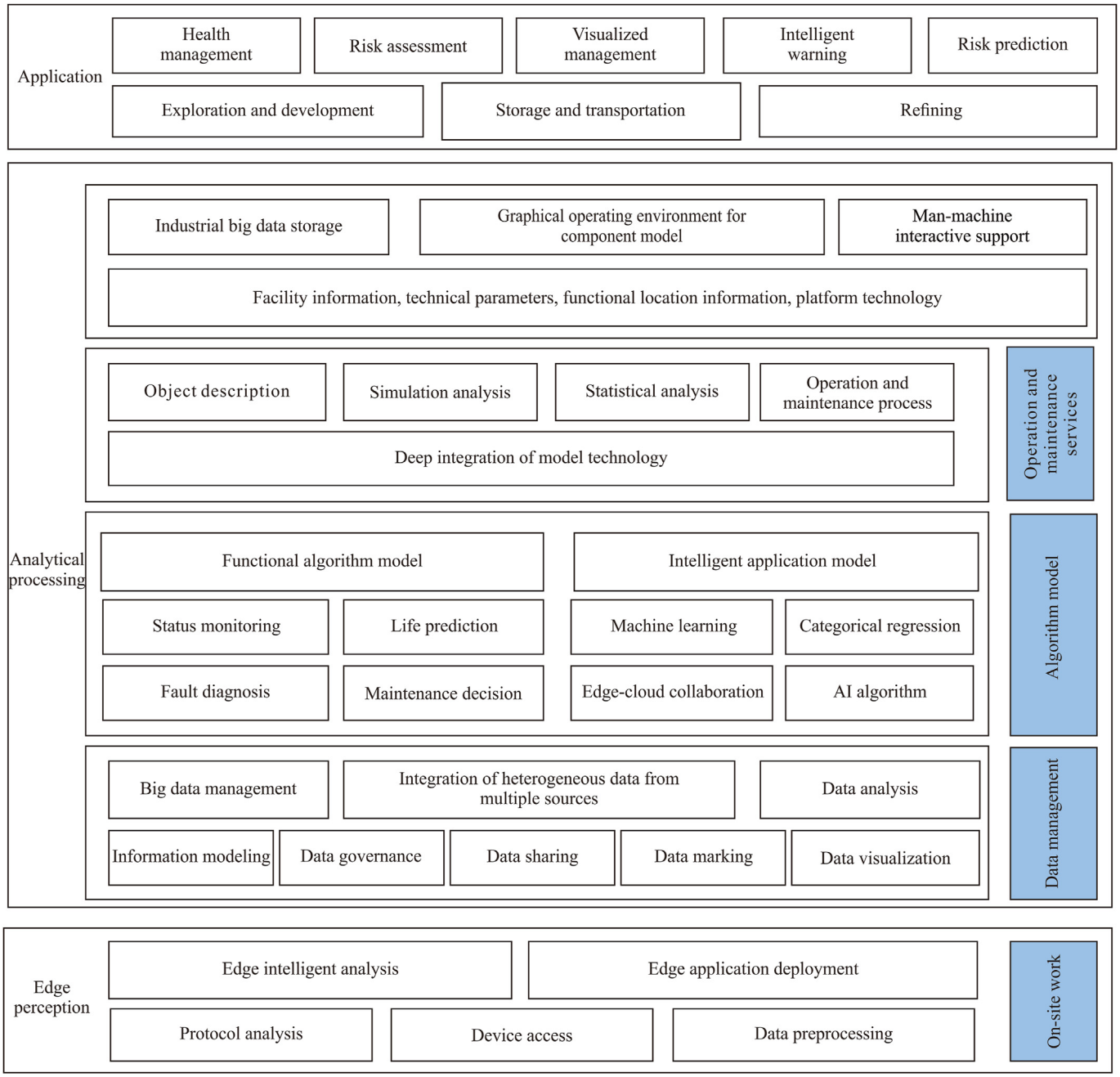


Fig. 1. Framework of intelligent safe operation and maintenance technology for oil and gas production.

By promoting the integration and innovation of oil and gas production with intelligent technology, potential dangers are fundamentally eliminated and the essential safety level of key core links in oil and gas production is improved, ultimately leading to safer development of oil and gas production systems.

The normal and stable operation of production equipment and facilities is the key to oil and gas systems [16]. Intelligent safe operation and maintenance provide technical support for on-site monitoring, fault warning, fault diagnosis, status evaluation, and other functions of critical equipment. There are various operations in the oil and gas production process, and the on-site situation is complex. Typically, there are multiple risk interference effects between operations, and the operational risks change dynamically [17]. Therefore, it is necessary to implement intelligent safe operation and maintenance systems in all key risk management and emergency response measures, as this will minimize the probability of accidents during the operation process. Oil and gas production covers the entire industrial chain from drilling and extraction to transportation, storage, refining, finished product processing, sales, and other upstream, midstream, and downstream industries, as shown in Fig. 2. Therefore, it is necessary to establish a full factor oil and gas production safety framework.

There are six factors that affect the stable operation of oil and gas production systems: (1) human, (2) equipment, (3) material, (4) technology, (5) environment, and (6) management. By considering these factors comprehensively, intelligent safe operation and maintenance can achieve safe production, improved quality and efficiency, and reduced costs. Based on monitoring data relating to the status of oil and gas production equipment and facilities, an intelligent safe operation and maintenance system can acquire performance indicators, speculate on key nodes of equipment failure, predict potential failure links, and ultimately ensure the safety of oil and gas production equipment. By collecting and sorting data, the intelligent safe operation and maintenance system can identify hazards, determine the degree of risk, and provide specific risk-mitigation measures to ensure the safety of oil and gas production. By constructing a production process model, an adaptive warning analysis method can be established to simulate actual working conditions and achieve risk prediction, thereby ensuring the safety of the oil and gas production process.

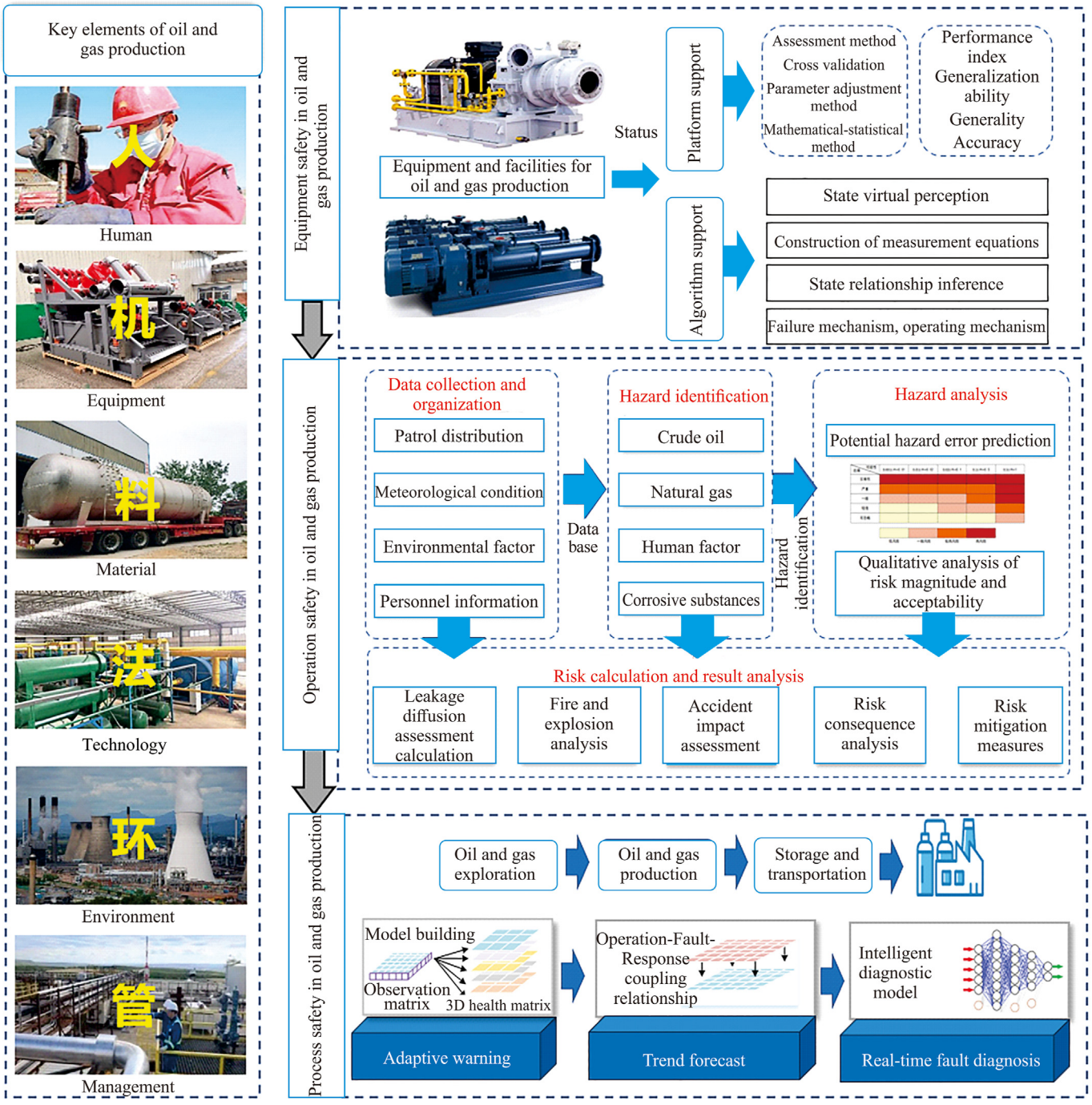


Fig. 2. Framework for full-factor oil and gas production safety.

### *2.3. Problems and challenges in intelligent safe operation and maintenance of oil and gas production*

To date, there has been considerable research on the intelligent and safe operation and maintenance of oil and gas production. However, many problems and challenges remain in the acquisition and analysis of multi-source data relating to oil and gas field production safety, multi-dimensional and multi-scale risk evolution in oil and gas fields, and collaborative optimization and implementation on the industrial internet. This paper outlines three major challenges and four key issues that urgently need to be addressed in intelligent safe operation and maintenance.

The three major challenges are as follows: ① Difficulty of technical research. Typically, the traditional operation mode suffers from the fragmentation of data, prevalence of information silos, long development cycles, and inability to respond flexibly and quickly to new demands. This makes it difficult to satisfy the future demands for production and digital transformation. ② Weak ubiquitous perception. With numerous links and diverse risk factors, oil and gas production systems are very complicated. In certain specific business scenarios, intelligent exploration can be achieved, but few perception technologies can be applied. A system's ubiquitous perception ability needs to be further enhanced. ③ Difficulty of platform unification. The development and application of intelligent algorithms based on specific business scenarios are complicated by inconsistent data standards and isolated application systems [18]. Under such circumstances, it is difficult to construct a unified platform for data collection, transmission, application, centralized storage, and sharing.

At present, there are four key issues in intelligent security operation and maintenance.

**1) Evolution mechanism and risk characterization of multidimensional and multi-scale risks in the oil and gas industry.**

The failure or abnormality of a single item of production equipment may lead to the failure of other equipment, causing the fault to propagate. Therefore, it is necessary to analyze the forms and rules of risk propagation across space [19]. By studying the risk propagation mechanism, it is possible to clarify the directionality and dependency relationships within the system, evaluate the risk evolution status, and construct a risk evolution model. This clarifies the causes and evolution processes of risks, and elucidates the risk propagation mechanism across devices, space, and time, ultimately revealing the risk evolution mechanism.

**2) Multi-source heterogeneous big data integration and analysis in oil and gas field production safe operation and maintenance system.**

Efficient data mining, analysis, and processing are prerequisites for comprehensive analysis of system operation conditions, which includes not only the safety of physical equipment, but also the overall changes caused by data anomalies. Therefore, the first step is to determine the specific characteristics of multi-source heterogeneous data and establish key data acquisition methods from two dimensions: logical reasoning and data mining. Using multi-modal deep learning, the integration of multi-source heterogeneous data can be achieved. This overcomes the integration difficulties caused by data heterogeneity [20] and sparsity, highlights the complex fusion and analysis of heterogeneous data, and clarifies the mechanism of multi-source heterogeneous big data integration analysis.

**3) Edge-cloud collaborative safe operation and maintenance knowledge generation on industrial internet.**

Edge-cloud collaboration technology can promote the development of intelligent operation and maintenance levels in production systems [21]. Establishing a unified, centralized, and elastic cloud base enables the centralized deployment, integration, and sharing of applications in production systems, and a standardized cloud operation and maintenance environment. Based on edge-cloud collaborative computing technology, operation and maintenance knowledge production mechanisms can be supported in different scenarios. Deploying a unified, open, and standardized oil and gas data platform permits the establishment of a universal, open, and scalable intelligent and safe operation and maintenance platform. Based on perception, interconnection, and data fusion, it then becomes possible to establish an operation and maintenance knowledge generation mechanism for key processes, such as real-time monitoring, intelligent diagnosis, automatic disposal, and intelligent optimization of production.

**4) Digital-twin inference and decision-making for operating and data integration of oil and gas production equipment.**

At present, reasoning decisions based on device status are conducted separately and independently. The comprehensive use of equipment status, operational performance, and risk assessment techniques to formulate optimized maintenance decisions requires urgent consideration. Consequently, it is necessary to establish fault diagnosis, risk warning, and performance evaluation models based on the integration of equipment mechanisms and real-time data [22]. Digital-twin technology can automatically raise alerts about equipment faults and predict performance conditions. This enables the integrated operation and maintenance control of equipment functions, performance, and risks, and achieves closed-loop management of equipment throughout the entire lifecycle. By constructing a data-driven digital-twin failure model, it is possible to gradually expand the available dataset, achieve fault-tolerant, self-learning, and self-organizing parallel processing, and establish a digital-twin inference and decision-making mechanism that integrates mechanisms with data.

## 3. Intelligent safe operation and maintenance technology for oil and gas production systems

We have established a six-stage intelligent safe operation and maintenance technology for oil and gas production systems (Fig. 3). Starting by solving practical problems, the system clarifies the core elements, realizes the main functions, and solves key tasks. Six key technologies are employed to support the construction of the system, allowing five main tasks to be achieved. The system has four analytical capabilities, including three core elements that complete two major directional changes and ultimately achieve a basic goal. From this, a bottom-up intelligent and safe operation and maintenance technology for oil and gas production systems is formed.

### 3.1. Fundamental goal

The fundamental goal of intelligent safe operation and maintenance is to provide a solution for safety assurance, quality assurance, and efficiency improvement of the entire oil and gas production system. This is achieved through standardized, digitized, visualized, automated, and intelligent management methods. By developing a unified intelligent safe operation and maintenance platform, it is possible to realize unified monitoring and judgment, unified linkage and emergency response, and unified processing to enhance the level of operation and maintenance management.

### 3.2. Major directional changes

Using industrial internet technology and artificial intelligence, an intelligent safe operation and maintenance system needs to complete the following two technological transformations: ① from sensory-based to data-based equipment condition identification; and ② from experience-based to knowledge-based decision-making. By shifting from manual production scheduling, diagnosis, inspection, and empirical judgment to automatic push, intelligent diagnosis, intelligent inspection, and intelligent analysis, the operation and maintenance efficiency and accuracy can be effectively enhanced.

### 3.3. Core elements

The core elements of intelligent safe operation and maintenance technology are reflected in the following aspects: ① Data perception is similar to the five sensory functions of humans, that is, external information is obtained through sensing technology. ② The algorithm is equivalent to the human brain and can analyze and judge external information through mechanism models, data-driven models, and other technologies. ③ A software platform is equivalent to a human body, supporting the transformation of business applications towards a “modular, iterative” industrial application model. The three are interrelated and mutually supportive, with the data perception as the foundation, algorithm patterns as the core, and software platforms as the carriers.

### 3.4. Analytical capabilities

The four analysis capabilities of intelligent safe operation and maintenance include: ① Real-time monitoring: By using a multi-dimensional space-air-ground monitoring system, it is possible to comprehensively perceive the operational risks of oil and gas production systems, visually analyze the operational status, and achieve data aggregation and statistical analysis. ② Diagnostic evaluation: By utilizing intelligent modeling methods such as big data and mechanism models, it

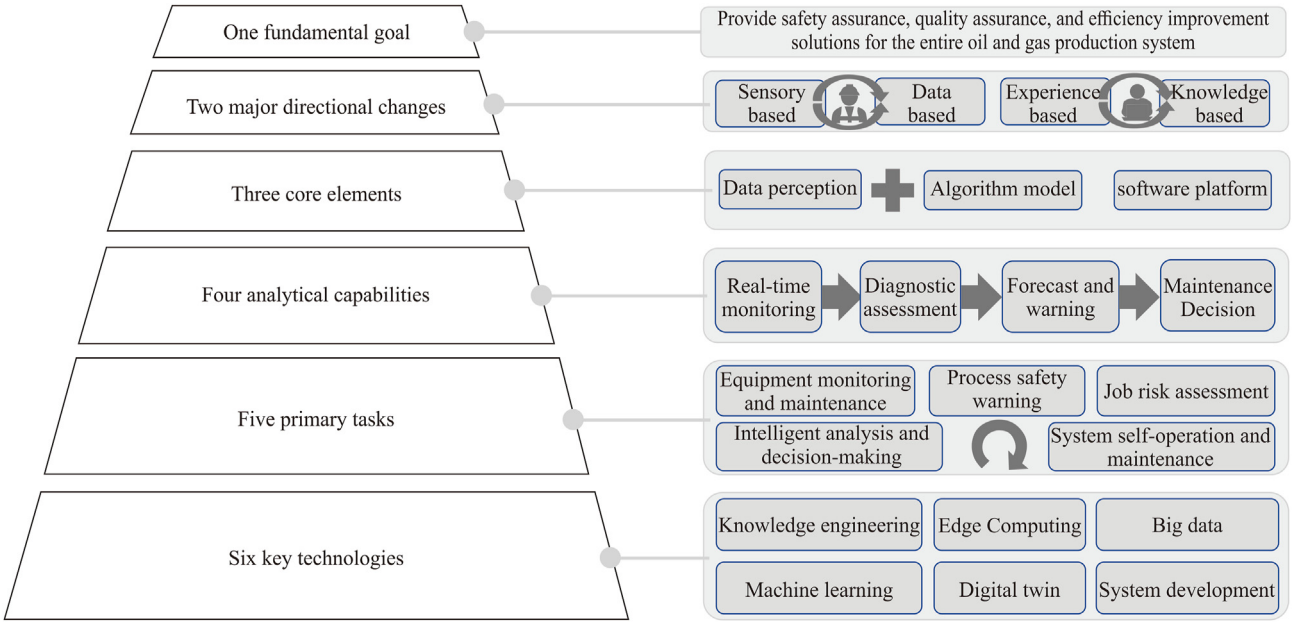


Fig. 3. Intelligent safe operation and maintenance technology for oil and gas production system.

is possible to comprehensively analyze factors that affect equipment operation status, economy, and reliability, and accurately diagnose and evaluate health and abnormal conditions. ③ Predictive warning: By analyzing the possibility and timing of future anomalies, early warnings can be issued to identify the type and location of anomalies. ④ Maintenance decisions: By analyzing big data on operations and maintenance, optimization decision-making methods can be established, scientific and reasonable maintenance decisions and emergency handling suggestions can be provided, and the level of intelligence in operations and maintenance can be enhanced.

### 3.5. Primary tasks

The main tasks of intelligent safe operation and maintenance systems include: ① Equipment monitoring and maintenance. The normal and stable operation of equipment and facilities is crucial for oil and gas production, and intelligent safe operation and maintenance systems can provide technical support for the monitoring, warning, diagnosis, and evaluation of key equipment on the production site. ② Process safety warnings. Oil and gas production systems involve complex processes and have high safety requirements. An intelligent safe operation and maintenance system must have the ability to detect and independently handle abnormal events in the production process in a timely manner. ③ Risk assessment. The risks inherent to oil and gas production change dynamically. Multiple risk inferences require intelligent safe operation and maintenance systems to carry out key risk control and provide emergency response measures to minimize the possibility of accidents during the operation process. ④ Intelligent analysis and decision-making. Big data management, integration, and intelligent decision analysis should be realized through oil and gas production data detection and analysis, providing technical support for oil and gas production system operation and maintenance. ⑤ Self-operation and maintenance of the system. The operation and maintenance system should have the ability to withstand abnormal events through the process of determining, defending, attributing, and tuning its own safety threats.

### 3.6. Key technologies

Covering knowledge engineering, machine learning, edge computing, digital twins, big data, system development, and other key technologies, safety operation and maintenance provides basic technical support for the intrinsic safety, quality, and efficiency of oil and gas production systems. The implementation framework is based on the six key technologies shown in Fig. 4. By fully leveraging the advantages of each key technology, the key elements of oil and gas production will be empowered, thereby achieving safety assurance, quality assurance, and efficiency improvements.

Big data technology includes system informatization data processing, external cross-border data, and industrial internet-of-things data integration. The integration of data analysis, data science, and automation can be achieved using machine learning technology. Big data technology and machine learning technology can enhance the analytical and computational capabilities of digital-twin technology, which emphasizes the consistency of data sources throughout the entire lifecycle of the system. The accuracy of product descriptions is ensured by digital twin, thus providing technical support for the full lifecycle operation and maintenance of oil and gas production systems, and realizing full lifecycle operation monitoring. System development based on platform technologies such as microservice containerization and data middleware can be used to develop industrial intelligent application development frameworks, creating a flexible and open intelligent business environment. The advantages of knowledge engineering, such as high visualization, strong correlation analysis, and identification of hidden relationships, facilitate the analysis, reasoning, and decision-making on specific problems. Knowledge engineering technology can be used to form domain knowledge bases, while edge-computing technology can be used to provide convergent network, computing, and storage capacity. Finally, the application of intelligent safe operation and maintenance technology in oil and gas production systems can be realized in terms of real-time monitoring, early warning, risk assessment, and other functions.

## 4. Typical application of intelligent safe operation and maintenance technology for oil and gas production

The close connection between the upstream, midstream, and downstream industrial chains means that oil and gas production has a distinct structure and transmission effect. Typical production scenarios include drilling and extraction, storage and transportation, and refining and chemical engineering in the upstream, midstream, and downstream. Intelligent safe operation and maintenance technology can be used to achieve status monitoring, health management, risk assessment, visual management, intelligent warning, and risk prediction.

### 4.1. Oil and gas drilling and production

The drilling and exploration of hydrocarbons in deep formations, deep water, and unconventional oil and gas resources involve complex processes and harsh working conditions. Oil and gas drilling and exploration operations are susceptible to multiple coupling accidents in harsh environments (e.g., high temperatures, high pressures, acidity, and open seas), posing great challenges for early warning and emergency rescue [23]. Through intelligent safe operation and maintenance technology, intelligent fitting of reservoir models and intelligent warning of oil and gas production safety can be achieved. This will improve the level of drilling and production technology, ensure the safety of oil and gas production systems, and help prevent accidents.

Based on intelligent safe operation and maintenance technology, the collaborative construction of drilling and mining sites, ground/underground integration, and geological

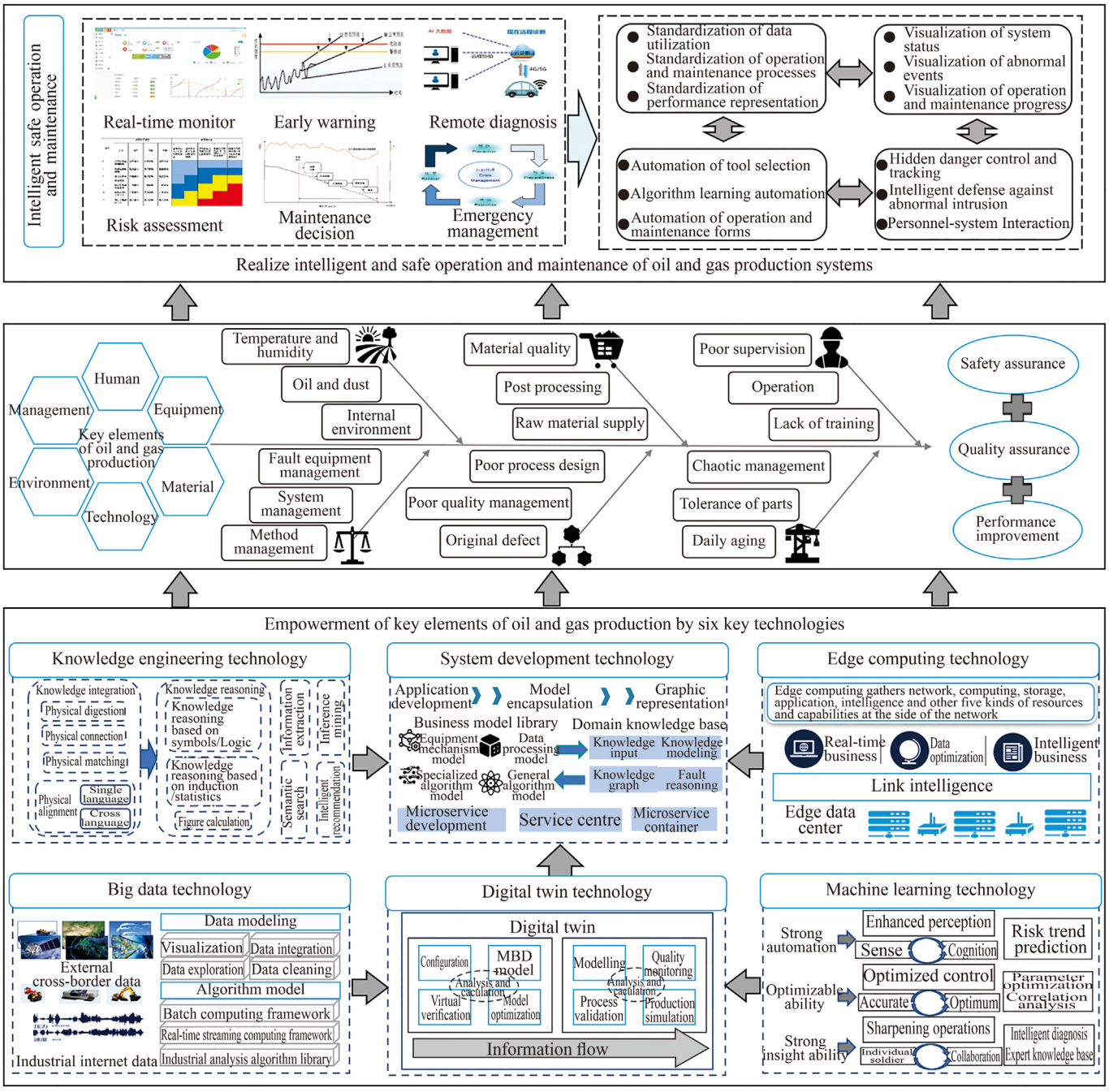


Fig. 4. Framework diagram for intelligent safe operation and maintenance of oil and gas production systems.

engineering integration can be carried out so as to improve the level of drilling, mining, operation, and maintenance. By developing an integrated intelligent safe operation and maintenance platform for oil and gas drilling and exploration, real-time and comprehensive perception can be achieved on oil and gas production sites, thereby transforming production and operation methods and minimizing operational costs and risks. By creating a virtual environment for drilling and development, it is possible to build comprehensive datasets and realize full connection of drilling and production data. This enables intelligent and safe operation and maintenance of oil and gas drilling and production scenarios based on multi-discipline, multi-dimensional, multi-temporal, real-time and complete global data. By utilizing intelligent safe operation and maintenance technology to establish a data analysis and intelligent diagnosis system, real-time data on vibration, temperature, pressure, flow rate, and other key equipment can be obtained. Through fault prediction analysis, it is possible to accurately determine the cause of a fault, study methods for identifying abnormal operating conditions in the oil and gas drilling and exploration process, and conduct safety evaluations of the extraction process. Thus, intelligent risk classification and control can be achieved, and potential problems can be identified in advance.

### 4.2. Oil and gas storage and transportation

In the field of oil and gas storage and transportation, pipeline leakages are generally identified by monitoring changes in parameters such as pressure and flow rate. The leakage monitoring capabilities need to be improved. A lack of derivative disaster assessment models for oil and gas pipelines and stations means that the accuracy of risk assessment predictions is low. Systematic integrity evaluation methods are yet to be developed for the inspection and maintenance of storage tanks [24]. To solve these problems, intelligent safe operation and maintenance technologies are required. By formulating a reasonable operation and maintenance plan, simulating and analyzing the decision-making effect, and tracking and managing the decision-making implementation process, it is possible to reduce the decision-making risk, improve the macro decision analysis ability, achieve predictive maintenance, effectively cut maintenance costs, and minimize the risk of unplanned downtime.

Intelligent safe operation and maintenance technology should make the oil and gas storage and transportation process safer in terms of process risk evolution, real-time risk perception, intelligent warning technology, and key facility health monitoring. To address the challenges of risk monitoring and early warning in the oil and gas storage and transportation process, a remote monitoring and predictive maintenance platform combining edge-cloud technology is required, integrating business data and spatial data. Based on perception, computation, and modeling, it is possible to achieve interactive mapping between physical and virtual spaces for intelligent applications. By fully utilizing monitoring data in actual production, intelligent safe operation and maintenance technology can analyze key hydraulic and thermal processes during oil and gas storage and transportation. The analysis of big data allows such a system to achieve rapid and accurate fault diagnosis, timely risk warning, and real-time process monitoring, as well as improving the safety of the entire process of oil and gas storage and transportation.

### 4.3. Oil and gas refining and chemical engineering

Oil and gas refining and chemical engineering suffers from resource dispersion and lack of coordination, partly because of the large production scale and complex processes of large refining enterprises. In addition, the refining process is complex, and operational control is difficult because of the involvement of flammable and explosive materials. Therefore, the safety problems associated with refining have gradually developed into a complex problem involving multiple media [25]. Conventional operation and maintenance technology not only improves the production efficiency and management efficiency of refining and chemical enterprises, but also introduces safety hazards.

By creating a real-time model of a refinery, intelligent safe operation and maintenance technology can provide dynamic alerts driven by virtual and real data synchronization. Personnel in the accident area can receive alerts and evacuation guidance, while initiating an accident response mechanism. To address the difficulty of risk warning for key refining equipment, digital-twin technology and big data can be combined to establish a digital-twin model for equipment. This enables dynamic warnings driven by virtual and real data synchronization. Based on real-time mapping and virtual sensing technology, complex fault diagnosis and tracing technology can address the problem of fault diagnosis and management faced by refining equipment, achieving virtual and real fusion diagnosis and early warning. To manage the health of refining equipment, a multi-source monitoring data feature indicator system can be established based on big data, exploring the implicit relationship between feature indicators and equipment deterioration status. Such a system could also construct an equipment health assessment scale and understand equipment health conditions in real time.

## 5. Development trend of intelligent safe operation and maintenance technology

At present, the safety of oil and gas production systems includes not only the safety of physical equipment, but also changes in the comprehensive situation of the system caused by network attacks and data anomalies. The diversified characteristics of production safety risks increase the difficulty of identifying potential risks, and make the safety situation more severe. These technological and situational changes have led to the development of intelligent safe operation and maintenance towards intelligent decision-making, proactive prevention, and comprehensive information and physical safety.

### 5.1. Development of safe operation and maintenance towards intelligent decision making

Intelligent safe operation and maintenance can identify safety risks that may pose a threat to system safety, with big data technology used to analyze massive amounts of security data. However, there are issues with unclear safety risk elements and risk evolution mechanisms in the analysis of functional components or application layers of the system. Thus, there is no theoretical framework for describing the cross-domain risk transmission and evolution of oil and gas production systems. Intelligent safe operation and maintenance should develop towards intelligent perception, data chain utilization, and intelligent decision-making. By conducting logical and knowledge-based reasoning, difficult-to-measure physical quantities can be estimated, potential security threats can be predicted and judged, and the accurate warning and handling of security risks can be improved.

### 5.2. Transition from risk monitoring to proactive prevention

Abnormal operation of the oil and gas production system itself can lead to data anomalies. Therefore, accurately detecting system abnormal behavior and confirming the source is the key to active detection and defense. A lack of

information updates has led to uncertainties and low accuracy levels in long-term forecasting. In intelligent safe operation and maintenance systems, the transformation from passive safety protection to proactive defense can be realized by establishing active prevention safety technology. By utilizing mixed perception information and risk prediction models, intelligent safety reasoning and decision-making techniques for oil and gas production systems can be implemented, risk factors can be identified, and different levels of risk factor system frameworks can be constructed. Elaborating on the basic forms of risk formation and evolution propagation enables comprehensive and effective diagnosis and accurate prediction of oil and gas production and operation.

### *5.3. Evolution from system safety to comprehensive information physical safety*

The information safety threat to oil and gas production information systems interacts with engineering safety risks to the physical system, creating a systemic comprehensive security problem. The unclear coupling mechanism and control factors mean that there is a lack of active defense and control techniques. Therefore, intelligent safe operation and maintenance should clarify the information−physical coupling mechanism, reveal the cross-domain risk evolution, and construct a perception/evaluation strategy. By establishing an anomaly detection and warning technique for oil and gas production systems under information−physical interactions, a theoretical and methodological system for risk analysis and control can be formed. This is of great significance in the development of intelligent safe operation and maintenance technology.

## 6. Conclusions

There is an urgent need for the digital transformation of oil and gas production, operation, and maintenance. Thus, it is necessary to study the integration and application of new-generation information technologies in intelligent oil and gas safe production, establish intelligent safe operation and maintenance technology, and improve the level of intelligent safe operation and maintenance. These are the inevitable trends for improving the quality and efficiency of oil and gas production and promoting green transformation and development.

Key technologies such as knowledge engineering, machine learning, edge computing, digital twin, big data, and system development can be combined to build an intelligent safe operation and maintenance technology for oil and gas production systems. Encouraging intelligent decision-making, proactive prevention, and comprehensive intelligent safe operation and maintenance will promote the digital upgrading of conventional oil and gas production systems, the development of digital and intelligent oil and gas production operation and maintenance methods, and build a new model of intelligent safe operation and maintenance.

Oil and gas production enterprises should vigorously develop intelligent and safe operation and maintenance, not only ensuring their own energy production and supply, but also effectively responding to international market competition. In a significant global economic recession and faced with the long-term instability of international oil prices, vigorously promoting the intelligent transformation of the oil and gas industry has prominent strategic and practical significance. Taking the intelligent and safe operation and maintenance of oil and gas production as a basis, relevant research can provide references for the intelligent development of the world's oil and gas industry, promote intelligent manufacturing services for industrial enterprises, and accelerate the digital and intelligent transformation of the manufacturing industry. This is of great significance in both economic and national security terms.

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## Conflicts of interest

The authors declare that there is no conflicts of interest

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