In-Depth Discussion on the Construction of Security Collaborative Management and Control System Based on Digital Twins and Intelligent Sensing in the United Nations Clean Coal Project

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ABSTRACT With the rapid development of Electromagnetic Waves, Antennas and Propagation technologies, communication-enabled sensing infrastructures and wireless monitoring networks have become fundamental components for intelligent industrial safety management. To address the challenges of dynamic risk perception, fragmented information exchange, and delayed emergency response in large-scale clean coal projects, this study proposes a security collaborative management and control framework integrating digital twins and intelligent sensing under a unified "one platform, two mappings, three linkages" architecture. The framework combines digital twin synchronization, IoT sensing, UWB–Bluetooth positioning, AI-based behavior recognition, edge computing, and multi-source data fusion to establish real-time interactions between physical entities and virtual models for dynamic risk prediction and collaborative decision-making. A quantitative risk assessment model and collaborative response index are further introduced to support adaptive warning generation, intelligent emergency dispatching, and closed-loop safety management. Experimental implementation demonstrates an early intervention rate of 93.9%, hazard identification accuracy above 95%, emergency response time below 5 minutes, and resource scheduling accuracy exceeding 96%, confirming the effectiveness of the proposed architecture. The integrated framework provides a scalable methodology for communication-oriented sensing, distributed information propagation, intelligent monitoring, and cyber–physical system coordination, offering valuable engineering references for smart industrial infrastructures and Electromagnetic Waves, Antennas and Propagation applications.

INDEX TERMS digital twin, intelligent sensing, distributed information propagation, communication-oriented monitoring

I. INTRODUCTION

AGAINST the backdrop of global energy structure transformation, clean coal technology has become a key path to balance energy security with the ecological protection required for sustainable synthesis, and the United Nations continues to promote its demonstration and international application. This transition ensures a stable and low-carbon energy foundation for the high-intensity processes of manufacturing and advanced material production. However, large-scale coal chemical projects, due to their long process flow, highly hazardous materials, and high equipment density, have long faced safety management challenges such as dynamic risks, lagging supervision, and fragmented multi-systems [1,2]. The inability of traditional approaches to safety management (e.g., manually inspecting or using static lists) to keep pace with actual changing conditions makes it impossible to effectively manage real-time risks in an evolving universe. As a result, bottlenecks—such as the inability to measure risk consistently, to contain that risk, and to be responsive to that risk—exist with the current methods of managing workplace safety. Therefore, there is an urgent need for digital structures to manage and govern workplace safety [3,4].

Yulin Energy Chemical, as a UN clean coal technology demonstration enterprise, addresses safety management issues i.e. dynamic monitoring of 43 major hazard sources, fault prediction for 510 key pumps, controlling high risk special operations in full, and coordinating emergency measures across departments. Each of these safety issues is critical to establishing an inherent safety level for businesses, as well as demonstrating credibility and scalability of clean coal technology around the world, with significant value for engineering practice and demonstrating an industry's use of this technology [5,6].

There has been quite a bit of research recently trying to use new technologies - like digital twins, IoT sensors, and AI - in the world of industrial safety. Industrial safety is extremely important, but there are still significant gaps in this area of research, especially with regard to the safety of data being transmitted and privacy protection of individuals, where IoT technology can offer valuable assistance [7,8]. Digital twin technology is especially powerful to aid with real-time industrial monitoring, immersive safety training, and predicting risk to eliminate potential industrial safety issues [9,10]. One of the most important aspects of industrial safety management is to use artificial intelligence to enhance safety management. This allows for pro-actively identifying and lessening possible risks and optimizing the consumption of energy as well as enhancing operational efficiency [11,12]. A few researchers have suggested using visual representations of risks at a factory site in order to manage these risks and to reduce incidents [13,14]. Other researchers are using heatmaps and risk based-contingency maps in order to determine which contingency events most strongly affect the operational risk and build associated methods accordingly [15,16]. Research has used LSTM (Long Short-Term Memory) networks for equipment failure prediction, which can predict machine failures and performance degradation in specific factories, reducing losses caused by downtime [17,18]. 5G-enabled edge computing can efficiently transmit information and provide real-time data processing and analysis [19,20]. Most accidents are attributed to human error, and virtual reality technology, as an effective way to improve human factors, allows employees to gain practical experience in a safe and controllable environment [21,22]. Blockchain can provide reliable, secure, and decentralized information for different industrial sectors, providing reliable technical support for industrial safety management [23,24]. However, existing methods often focus on verifying single technical points, lacking deep coupling with safety management processes, and generally suffer from the problem of "emphasizing technology over management." Risk warnings and handling instructions are disconnected; data silos are not truly broken down; it is difficult to support the improvement of management efficiency in smart management.

As the main entity undertaking the world's first integrated utilization project of coal, oil, and gas resources, Yanchang Petroleum Yulin Energy Chemical is awarded the title of "UN Clean Coal Technology Demonstration and Promotion Enterprise" by the United Nations in 2009. It anchors its safety value coordinates with "five hearts" and proposes to build a safety collaborative management and control system that integrates digital twins and intelligent perception, guided by the "five hearts" safety value coordinates. By employing a "one platform," "dual mapping," and "three linkages," the system systematically promotes the transformation of safety management from passive response to proactive prevention and control, and from local control to global collaboration. This approach addresses industry safety management challenges such as highly dynamic risks, lagging supervision, and fragmented multi-system operations, providing empirical evidence and technical frameworks for the clean development of high-energy-consuming sectors. It offers significant theoretical and practical implications for ensuring the continuous and safe operation of advanced manufacturing machinery on a global scale.

II. BACKGROUND AND OBJECTIVES OF THE CONSTRUCTION OF THE DIGITAL TWIN AND INTELLIGENT SENSING SAFETY SYSTEM IN YULIN ENERGY CHEMICAL INDUSTRY

REAL-WORLD PAIN POINTS IN SAFETY MANAGEMENT OF LARGE-SCALE COAL CHEMICAL ENTERPRISES

The Yulin Energy Chemical Group has developed enterprise-wide mechanisms to dynamically identify risks within the enterprise as a result of long process chains and rapid changing sources of risk. The mechanism classifies and assesses each of the 43 major hazard sources based on their actual operating conditions and classification types, and defines a person or group responsible for each hazard source and specifies the time frame to respond to each phase of a hazard source event. To address the lag associated with traditional forms of oversight, "clearing and settlement daily" are built into a verification system for assessing risk. Team Leads perform daily on-site confirmations using the high-risk daily push list from the system; Safety Officers perform random audits; and any unclosed items are considered for elevation to supervision. In an effort to eliminate data silos from multiple systems, a unified data governance standard has been developed so that the uniform standards are met across DCS (Distributed Control Systems), video surveillance, personnel tracking, providing a "relative" data connection and recognition of status in key work processes such as work permits, hazard rectification, and emergency response. As a result of these unifying standards, cross-departmental collaborative instruction can remain consistent, provide a traceable record for execution, and generally enhance response efficiency overall [25,26].

DIGITAL TRANSFORMATION STRATEGY GUIDED BY THE "FIVE HEARTS" SAFETY CULTURE

Yulin Energy Chemical instills the "Five Hearts" safety value orientation in its entire digital management processes, principally aiming at attaining "Zero Violations, Zero Defects, and Zero Injuries." It has integrated the principle of inherent safety into all facets of project management associated with the clean coal technology projects. A comprehensive intelligent monitoring system is established with a total number of 3,686 combustible and toxic gas alarms linked to the fire protection system. Alarm events are fired off both at the local site and in the central control room if gas concentrations are outside of acceptable limits. At the same time, there are 46 mobile high-definition cameras that have local storage systems in place to offer visual supervision of the complete scope of operations for the high-risk job type, and four intelligent inspection robots have been placed into service to help ensure there are no unmonitored areas that are hard to monitor manually. To bridge the gap between subjective culture and objective sensing, the "Five Hearts" values are operationalized into the digital twin through a set of "Safety Emotional & Behavioral Indicators" (SEBI). For instance, the "Unity" value is parameterized as a "Collaborative Response Coefficient" within the model, which monitors the synchronization of multi-departmental data flows, while "Comfort" and "Warmth" are translated into ergonomic and environmental stress thresholds for frontline personnel, ensuring the digital twin reflects not just machine status, but the human-centric safety state.

SYSTEM CONSTRUCTION GOALS: ACHIEVING "PRE-EMPTIVE CONTROL, SYSTEM COLLABORATION, AND INTELLIGENT RESPONSE"

Yulin Energy Chemical has established a dynamic mechanism for assessing risks associated with "pre-emptive control" by integrating high-risk activities into the pre-approval process. The system automatically confirms that all appropriate safety measures have been properly implemented before allowing a high-risk activity to proceed. If there are any deficiencies relative to requisite safety measures, the system prevents the activity from occurring. In terms of "system collaboration," rules are established for data sharing across departments, as well as task linkage rules between departments. The rules also define responsibility between departments and establish a specific timeframe to complete the required actions. The unified platform for managing these processes allows for automatic assignment of tasks, tracking of task progress, and notification of overdue tasks. Finally, for "intelligent response," standardized procedures are used to respond to anomalies. When an anomaly has been detected, the system automatically provides the guidelines for responding to the responsible individual and sends notifications to all other applicable personnel to ensure that response actions are uniform and executed in an effective manner.

III. "ONE PLATFORM, TWO MAPPINGS, THREE LINKAGES" SYSTEM ARCHITECTURE AND PRACTICE PATH

"ONE PLATFORM": UNIFIED DIGITAL TWIN MANAGEMENT PLATFORM

The construction of the unified digital twin management platform centers on the optimization of management efficiency, serving as a structured framework to address multi-headed management, fragmented information, and delayed command challenges [27,28]. The platform architecture is illustrated in Figure 1.

As shown in Figure 1, the method outlines how to identify and organize the management responsibilities, regulatory requirements and emergency response procedures associated with all major sources of hazards at a site and incorporates these into the logic of the platform in a systematic manner. Doing this means that each point of risk has a precise attribution, rules for how to handle it and the time period within which to respond to it. In terms of data integration, the method integrates business systems such as DCS, SIS (Safety Instrumented System), location tracking of personnel, video surveillance, gas detection and equipment management to create a set of data governance standards across all systems. To maintain the integrity of air-gapped Control and Safety systems, the platform utilizes unidirectional security gateways (Data Diode) and an OPC-UA based industrial security protocol suite (IEC 62443 standards compliant). This architecture ensures that data from the SIS and DCS flows into the digital twin platform for monitoring purposes without exposing the control networks to external write-requests or potential cyber threats. The resulting collection of disparate data is cleaned, aligned and classified in order to provide a complete set of safety data to support decision-making for management.

The platform employs a "one map, one list, one flow" management solution, utilizing the 3D digital representation of the facility as its single source of operational management. It combines live risk heat mapping, hazard distribution mapping, and emergency response mapping to allow management to "see all of this on one screen". The platform automatically combines work orders, Job Safety Analysis (JSA), monitoring personnel data and historical data regarding like processes to create dynamic risk notifications for high-risk operations and ensure verification of the implementation of protective measures. The operation is not authorized to commence if any aspect of the supporting standards has not been satisfied, thereby enhancing process controls at the source. A three-tiered collaborative dashboard is established for Command and Dispatch, which includes the factory, workshop, and team level. Task assignment, progress tracking and rectification verification are all executed via an online closed-loop process. The system automatically captures timeliness and quality across each of the steps within the process, and the resulting data is included in the performance assessments as a means of holding all parties accountable.

A tiered early warning and push system is used in the platform to promote greater transparency in management. In this system, general hazards are automatically assigned to the appropriate local staff members, and when they do not take care of a general hazard within the time required, the first warning is automatically routed to a supervisory level. A second tier of warnings can automatically go out to the

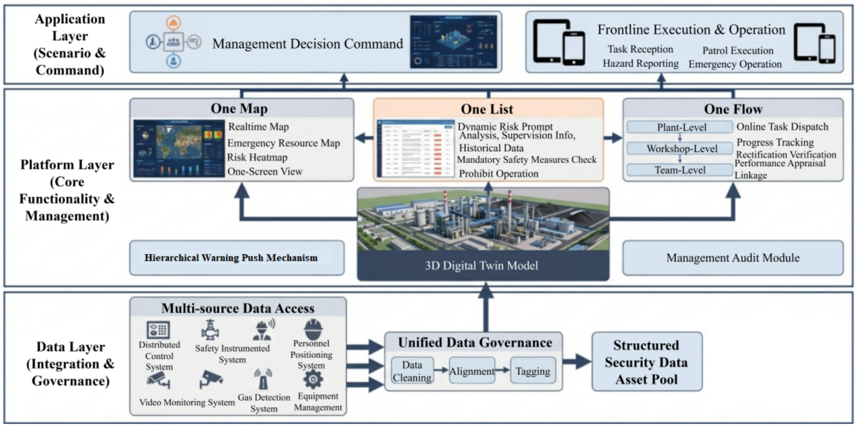

FIGURE 1. Unified digital twin management platform architecture diagram

safety director, production vice president, and the emergency command centre, sending critical information directly to key decision-makers when a major risk is created or abnormal operating conditions are encountered. The platform has a management audit module built into it and routinely generates risk trend, hazard reoccurrence, and response cycle time reports for each unit, assisting management with identifying weaknesses and optimizing resource allocation accurately.

To prevent "alarm fatigue" during simultaneous multi-zone incidents, the digital twin implements a dynamic priority matrix. Alarms are filtered and ranked based on toxicity levels, proximity to ignition sources, and prevailing wind direction sensors. High-priority "Critical Safety Alarms" are immediately visualized in the 3D twin with an automated suppression sequence, while lower-level alerts are batched to reduce cognitive load on operators.

"DUAL MAPPING": REAL-TIME INTERACTION BETWEEN PHYSICAL ENTITIES AND DIGITAL MODELS

Yulin Energy Chemical utilizes a dual mapping strategy that effectively connects the operational state of the real world to how management operates in the digital world. By utilizing this strategy, safety management has transitioned from a reactive to a proactive approach. For equipment and process management, Yulin Energy Chemical utilizes full lifecycle status dual mapping on 510 key pumps and 3686 gas alarms throughout the facility. Equipment operation data is synced in real-time to the digital twin platform via preprocessing at the edge nodes and compared with the process safety regulation criteria [29,30]. When equipment operation parameters drift outside the preset boundaries, not only does the system generate an early warning, but also automatically generates a handling suggestion package that contains equipment ledger, historical maintenance records, and similar fault cases as well as delivering it to equipment administrators and safety supervisors to guarantee that technical accuracy and management standardization has occurred during handling problems.

The use of personnel management and operational behavior management through a UWB (Ultra Wide Band) combined with a Bluetooth fusion positioning system, as well as video analysis, allows for real-time mapping of the location of personnel, movement trajectories, and operational actions in high-risk areas [31,32]. Specifically, the system leverages a lightweight YOLOv8-based object detection framework coupled with Pose-Estimation algorithms for behavior analysis. To address the challenge of complex occlusions in dense chemical plant environments, a multi-view fusion strategy is implemented, which synthesizes visual data from multiple overlapping camera angles and corrects spatial positioning using real-time UWB coordinates, significantly improving the recognition accuracy of partially obscured personnel. This system has a built-in compliance rule library that automatically detects common violations including not wearing personal protective equipment, entering a confined space without authorization, and performing hot work unsupervised; it then sends notifications to the appropriate person in charge, the team leader, and the safety officer. At the same time, all work process data is structured and archived as the basis for safety performance assessment and behavior trend analysis, promoting two-way calibration of individual behavior and organizational management. To quantify the risk evolution trend, a dynamic risk assessment model is introduced:

$$R(t) = \alpha \cdot \frac{dP(t)}{dt} + \beta \cdot H(t) + \gamma \cdot V(t) \tag{1}$$

In Formula (1), $R(t)$ represents the comprehensive risk index at time t; $P(t)$ is the degree to which the key process parameters deviate from the safety limit; $\frac{dP(t)}{dt}$ reflects its rate of change, reflecting the dynamic nature of risk; $H(t)$ is the exposure intensity of personnel in high-risk areas; $V(t)$ is the equipment health deterioration index; α, β, and γ are weight coefficients that are dynamically adjusted according to the characteristics of the work section and are periodically reviewed by the safety committee.

"THREE-LINKAGE": RISK WARNING, EMERGENCY DISPATCH, AND CLOSED-LOOP MANAGEMENT COLLABORATIVE MECHANISM

Yulin Energy Chemical has constructed a three-in-one collaborative mechanism of "early warning-dispatch-control" with management closed-loop and response efficiency as its core, opening up the entire chain of management from risk identification to rectification implementation. Regarding early warning linkage, the system implements graded responses based on dynamic risk assessment results: when the comprehensive risk index exceeds a preset threshold, it automatically triggers yellow, orange, and red level warnings, and simultaneously pushes them to local responsible persons, professional engineers, and safety management departments.

At the dispatch linkage level, the VR (Virtual Reality) emergency drill platform is deeply integrated with the actual combat command system. In daily operations, VR is used to recreate accident scenarios for immersive training and competency assessment of personnel [33,34]; once a real event occurs, the system automatically retrieves the corresponding contingency plan, combines real-time personnel positioning, meteorological data, and equipment status, intelligently generates the optimal evacuation route and resource allocation plan, and accurately dispatches tasks to the emergency response team via mobile terminals. The command center can simultaneously access the digital twin model, dynamically adjust response strategies, and achieve a closed-loop management system where "drills are real-world exercises, and real-world exercises are simulations." Regarding control and coordination, a fully automated mechanism for the entire process of hazard discovery, dispatch, rectification, verification, and archiving is established. The system automatically identifies hazards [35,36] through intelligent inspection robots, AI video analysis, and sensor networks, automatically generates structural work orders and assigns them to responsible units, setting rectification deadlines; if not completed within the deadline, the supervision level is automatically escalated and linked to performance evaluations. After rectification is completed, on-site images and verification data must be uploaded, and the loop can only be closed after AI comparison and confirmation. To quantify the effectiveness of coordination, a collaborative response index model is introduced:

$$C = \frac{1}{T}\sum_{i=1}^{n}\left(\omega_1 \cdot \frac{t_i^{plan}}{t_i^{actual}} + \omega_2 \cdot \frac{r_i}{R_i} + \omega_3 \cdot (1-\delta_i)\right) \quad (2)$$

In Formula (2), C is the collaborative response index, with a value range of [0,1], where a higher value indicates better linkage efficiency; T is the total number of events within the statistical period; t_i^{plan} and t_i^{actual} are the planned response time and actual response time of the i-th event, respectively; r_i is the actual number of emergency resources called up, and R_i is the resource quantity specified in the plan; δ_i is the i-th rectification overdue indicator; ω_1, ω_2, and ω_3 are weighting coefficients, satisfying $\omega_1+\omega_2+\omega_3 = 1$, and are reviewed and approved by the Safety Committee on a quarterly basis.

IV. PRACTICAL APPLICATION AND EFFECTIVENESS OF THE SYSTEM IN SAFETY MANAGEMENT

RISK CONTROL FROM "STATIC LIST" TO "DYNAMIC SIMULATION"

Yulin Energy Chemical has fully implemented a dynamic risk control mechanism based on digital twins. In terms of management, all major hazard sources and routine risk points in the plant are included in a unified risk database, and dynamic triggering rules are set according to dimensions such as process status, operation type, and environmental conditions. In order to enhance process control, the systems provide an automatic analysis of the operation time, site, qualifications of personnel, and current environmental conditions before issuing approval for a special operation. If any of these factors are found to be conflicting or invalid, the operation ticket is not issued. A digital twin of the operation's environment can continually monitor and record all actions taken by the personnel working on the operation, status of all equipment, and movement of gases in the operation. After an occurrence of a violation, such as not using the safety belt, not having supervision, or abnormal movement of gases, intervention directions are sent to the operator, supervisor, and team leader. The violation is also documented so that it can be used in future training and evaluation. At the management execution level, a "daily dynamic, weekly analysis, and monthly evaluation" system is implemented. Before the daily morning meeting, the system automatically generates a list of high-risk operations and prevention and control points for each unit, allowing teams to anticipate and control risks. Weekly, the safety management department leads the optimization of risk thresholds and response strategies based on the frequency of warnings, intervention effectiveness, and false alarm rate recorded by the system. Monthly, root cause analysis is conducted on recurring risks and high-frequency violations to drive revisions to procedures or engineering improvements. The number of dynamically identified risks and the rate of early intervention are shown in Figure 2 .

Figure 2 shows the number of dynamically identified risks and the early intervention rate in 2025. Across a year, more than 20,000 risks are dynamically assessed by the program, with an early intervention rate of 93.9%, peaking in February at 98%. The system determines risk levels by combining real-time data about equipment condition, employee behaviour and environmental factors, and then triggers tiered early notification and automatic intervention protocols. This results in a complete shift from a "post-event response" to a "pre-event management" safety paradigm.

FROM "MANUAL INSPECTION" TO "INTELLIGENT IDENTIFICATION" IN HAZARD MANAGEMENT

Yulin Energy Chemical has restructured its hazard management process from a traditional passive approach with

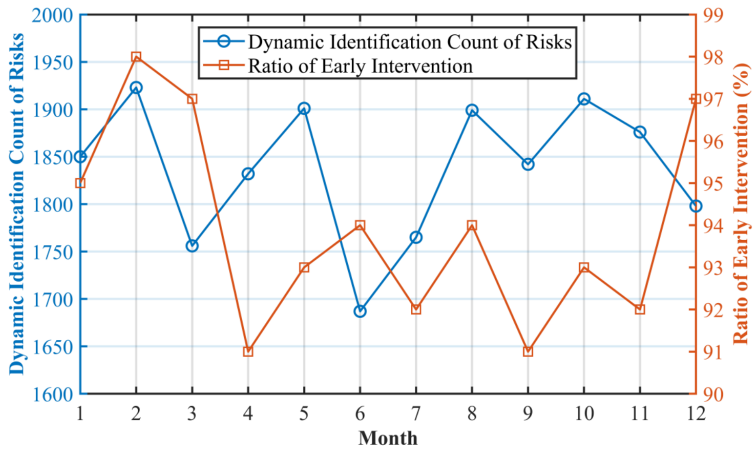

FIGURE 2. Number of dynamically identified risks and early intervention rate

manual inspections to an intelligent identification approach, moving towards proactive discovery, precise location and effective closed loop management of hazards. The entire operation is split into a number of intelligent inspection grids, and intelligent inspection robots are used to perform routine inspections of high risk areas according to predetermined routes and frequencies. To establish the practicality and traceability of the results of the hazard identification, a structured template for describing hazards has been established in the system; the type, severity and location of the hazard are electronically identified and documented by the system, thus eliminating the uncertainty and subjectivity of the manual reporting process. All identification results generate electronic work orders in real time, automatically assigning them to responsible work teams or professional engineers based on hazard level, and setting rectification deadlines: general hazards are closed within 24 hours, while major hazards trigger a special supervision mechanism, with direct intervention and tracking by the safety management department. During the rectification process, on-site photos or videos must be uploaded, and the system verifies the authenticity of the rectification through image comparison. The accuracy rate of the intelligent identification system's hazard type identification and early warning is shown in Figure 3.

As shown in Figure 3, the accuracy rate of hazard identification and early warning is 95% or higher for all types of hazards. This is due to the implementation of a full-chain responsibility system of "identification-dispatch-rectification-verification-assessment" in the management mechanism. The quantity and quality of hazard identification are incorporated into the performance evaluation of inspection units, emphasizing timely rectification and first-time acceptance pass rate, forming a two-way constraint. Simultaneously, monthly cluster analysis is conducted on high-frequency hazard types and recurring areas to identify weak links in management and promote a shift from "treating symptoms" to "addressing root causes."

Furthermore, a hazard management knowledge base has been established, structurally archiving identified hazards and their handling solutions. New employees can quickly search for similar cases through the platform, improving the problem-solving capabilities of frontline personnel. Management has a networked interface for monitoring overall hazards, the overall efficiency of the closed-loop system, and the overall resource throughput ratio at all plants at all times, and management can make continuous adjustments to the inspection strategy and employee training priorities based on those data.

EMERGENCY RESPONSE: FROM "CONTINGENCY PLAN DRILLS" TO "LIVE-FILM SIMULATIONS"

Yulin Energy Chemical has introduced a new management system to replace its outdated emergency management system based predominantly on textual plans, along with periodic simulated desktop exercise evaluations through in-person or remote desktop scenarios. New management system provides for a dynamic simulation model based on digital twins and real-time data. With respect to management, all accident scenarios across the site have been standardized and modeled. Each of these scenarios is furnished with a specific preparing process, resource list, evacuation plan, and command authority matrix, all included in one centralized emergency command database. On a daily basis, scenarios for individuals involved in managing emergencies use a Virtual Reality (VR) platform to engage in simulation drills forced to be completed quarterly. The VR-based platform captures performance data regarding individuals' behaviors while managing a scenario. This data includes the decision-making path, timeliness of instruction issue to participant, and validated resource allocation of participants' decision-making as the basis for generating team profile attributes, staff collaboration scores, and job competency assessments. Individuals occupying key positions are not allowed to oc-

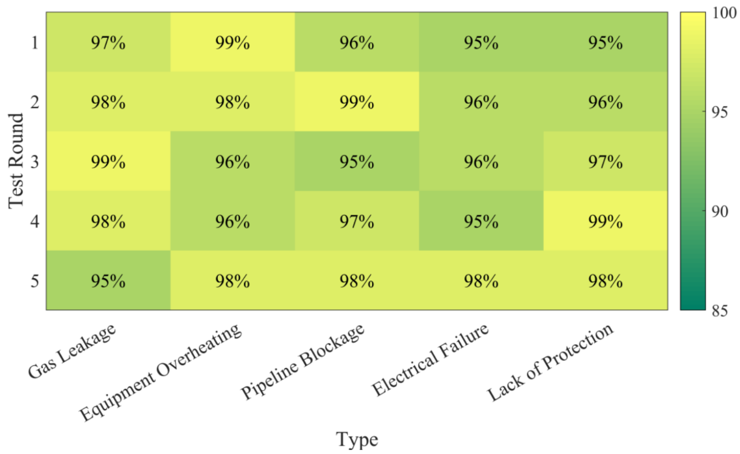

FIGURE 3. Accuracy rate of hazard type identification and early warning by the intelligent identification system

cupy their position when they fail the simulation evaluation.

An accident is recognized when a real incident takes place, at which point the system identifies the accident type, loads the correct simulation model and accesses real-time data (e.g. video on site, gas concentrations, personnel location, wind direction) that can be dynamically revising the original plan in that moment. The digital twin interface provides the command center with a view of the total area of effectiveness, trapped personnel, available resources and recommended response routes are updated on a digital twin interface so that they can accurately send task instructions to each emergency response team using mobile terminals. The system also starts a timer automatically to measure the timeliness of each key node; if a key node does not complete the assigned task within the time limit, an alert is issued. Figure 4 shows the emergency response time and resource allocation accuracy.

Figure 4 shows the performance of Yulin Energy Chemical in emergency response time and resource scheduling accuracy in 2025. As shown in Figure 4(a), the average emergency response time remains stable between 3.35 and 4 minutes throughout the year, with minimal overall fluctuation. Figure 4(b) shows that the average resource scheduling accuracy remains between 95.54% and 96.82%, with an annual average of 96.16%, indicating a high degree of consistency and reliability in the scheduling mechanism. After the implementation of this mechanism, the emergency response time is reduced to less than 5 minutes, and emergency response is transformed into dynamic adaptation, improving the organization's rapid response and collaborative combat capabilities in emergency situations, providing a solid guarantee for inherent safety.

SAFETY PERFORMANCE FROM "COMPLIANCE AND STANDARDS" TO "INTELLIGENT LEADERSHIP"

Yulin Energy Chemical moves away from the conventional approach to managing safety performance against minimum safety targets by developing an integrated intelligence-based methodology focused on data-derived information, controllable processes and continual improvement. Monthly safety performance targets are created by each production unit. An automatic capture of actual data concerning production activities occurs, with on-duty unit-level reports produced by the system in real time via a single platform. If safety performance targets are not met by any unit for two consecutive months, an automatic action of implementing special supervision occurs. This involves Yulin Energy Chemical's safety management department deploying a work group to assist in identifying the underlying issues, and providing a timeframe for alleviating the issue. A company using digital twin platforms for management support can completely eliminate the possibility of human intervention through automated collection and cross-verification of performance data. All performance data are simultaneously linked to the higher level regulatory platform so as to ensure that there is no discrepancy between data collected through self-inspection and regulatory standards, thus establishing uniformity of the source of the information. Accident log, major hazard source monitoring coverage, and response timeout for special operations are illustrated in Figure 5.

As shown in Figure 5(a), the recordable injury rate decreases to 0.12 in 2025, and the major hazard source monitoring coverage remains at 100% for a long period. Figure 5(b) shows that the response time for special operation violations intervention is less than 30 seconds. The intelligent collaborative mechanism supported by the "one platform, two mappings, three linkages" architecture continues to play a role, and the multi-source system ensures coverage without blind spots, laying a solid foundation for safety governance in clean coal projects.

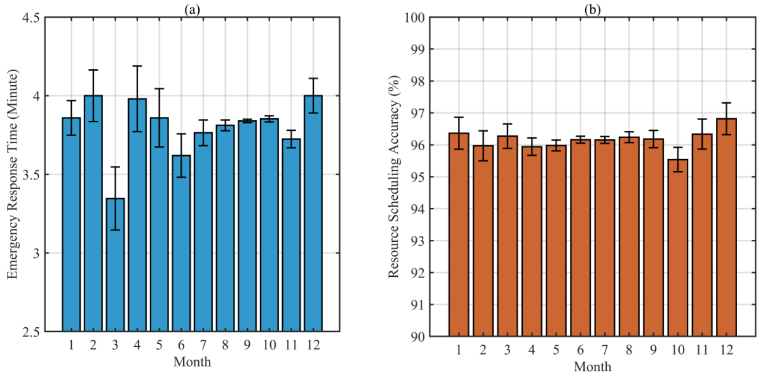

FIGURE 4. Emergency response time and resource scheduling accuracy in 2025: (a) Emergency response time; (b) Resource scheduling accuracy

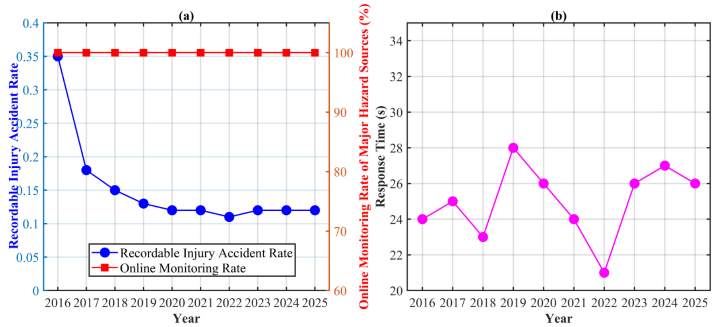

FIGURE 5. Analysis of core safety performance indicators: (a) Recordable injury rate and major hazard source monitoring coverage; (b) Response time for special operation violations intervention

V. SYSTEM CONTRIBUTION TO CLEAN COAL TECHNOLOGY SAFETY DEMONSTRATION

PROVIDING REPLICABLE "DIGITAL TWIN + SAFETY MANAGEMENT" MODEL FOR THE INDUSTRY

Yulin Energy Chemical System streamlines the management processes, division of responsibilities, and operating mechanisms under the "one platform, two mappings, three linkages" architecture, forming a standardized implementation manual covering core modules such as dynamic mapping rules for major hazard sources, closed-loop management processes for hidden dangers, and emergency simulation operation guidelines. Through internal multi-site promotion and application, its adaptability under different scales and process conditions has been verified.

YULIN ENERGY CHEMICAL BEING THE TECHNOLOGY DEMONSTRATION UNIT FOR THE UN CLEAN COAL PROJECT

Yulin Energy Chemical has achieved Level 1 compliance in safety production standardization and Level 6 compliance in ISRS (International Safety Rating System), establishing a three-tiered standardization system of "high-level planning - mid-level execution - grassroots implementation." The compliance rate of job operations, work environment, and management processes is 100%, and it has continuously passed national and provincial safety inspections, becoming an industry benchmark for safety compliance. Guided by advanced international standards and based on domestic compliance requirements, it deeply integrates the core advantages of the international safety production level quantitative assessment system, the safety production standardization system, and the QHSE (Quality, Health, Safety, Environment) management system, constructing an integrated management system covering 22 Level A elements and 78 Level B elements. This system wins the third prize of the National Safety Science and Technology Progress Award in 2019, providing solid institutional support for safety management.

SUPPORTING THE COORDINATED DEVELOPMENT OF SAFETY AND ENVIRONMENTAL PROTECTION UNDER THE "DUAL CARBON" GOALS

Yulin Energy Chemical integrates safety management and carbon emission management into a unified management system, establishing a "Safety-Low Carbon" collaborative working group at the organizational level to coordinate process optimization, equipment operation and maintenance, and emission monitoring. Through a digital twin platform, it integrates energy consumption, carbon emission intensity, and safe operation data, establishing a key unit energy efficiency-risk linkage assessment mechanism: joint diagnosis is implemented for high-energy-consumption and high-risk operating conditions, prioritizing technical upgrades; and a dual-track safety and environmental response process is simultaneously initiated for abnormal emission events. Furthermore, carbon emission indicators are incorporated into the safety performance evaluation of work teams, encouraging operators to optimize operating parameters while ensuring safety.

VI. EXPERIENCE SUMMARY AND FUTURE OUTLOOK

CORE EXPERIENCES

Yulin Energy Chemical adheres to three management principles in system construction. First, it deeply embeds the "Five Hearts" safety culture into digital processes, transforming cultural concepts into executable job behavior norms and assessment standards through system design. Second, a unified platform is used to connect data, processes, and responsibility chains, establishing a cross-departmental collaboration mechanism, clarifying the input and output interfaces and responsible entities for each link, and ensuring consistency in information flow, business flow, and decision-making flow. Third, technology can be used to serve business scenarios, with all intelligent sensing equipment deployments based on high-risk operation lists and historical accident root cause analysis. Regular joint business and technical reviews can be conducted to continuously optimize the matching degree between system functions and management processes, ensuring the system is practical, effective, and sustainable.

FUTURE DEVELOPMENT DIRECTION

Yulin Energy Chemical promotes safety management upgrades in three aspects. First, an AI model iteration management mechanism is established. By regularly reviewing the accuracy and false alarm rates of early warnings, the process, safety, and data teams jointly optimize the risk prediction logic, promoting the model's self-learning and adaptive capabilities. Second, the scope of safety collaboration is extended to the supply chain. Safety access and performance evaluation standards for contractors and suppliers can be formulated, and information sharing on work permits, personnel qualifications, and hazard rectification can be achieved through a unified platform, building an industry-level safety ecosystem. Third, a "safety-low carbon" integrated management position is established to connect safety operation data with the carbon emission accounting system. In decision-making such as equipment scheduling, maintenance plans, and energy efficiency optimization, safety risks and carbon emission impacts can be simultaneously assessed, promoting the development of smart factories towards a safe, green, and efficient integrated direction.

FUTURE MANAGEMENT DIRECTIONS BASED ON INDUSTRY-WIDE INTELLIGENT AND INFORMATION-BASED MEANS

As a UN Clean Coal Technology Demonstration and Promotion Enterprise, Yulin Energy Chemical deepens the integration of AI and IoT in the future, builds a risk prediction model with self-learning capabilities, and promotes the evolution of safety management from "responsive" to "adaptive." By expanding the coverage of digital twins, it achieves full-chain safety collaboration from the plant area to the supply chain, and relies on blockchain technology to ensure the reliable sharing of contractor operation data. Simultaneously, it promotes the deep integration of safety management and online carbon emission monitoring systems, establishes an intelligent decision-making module linking safety and low-carbon development, and achieves simultaneous assessment of safety and carbon emission impacts in process optimization, emergency dispatch, and other aspects. Relying on 5G and edge computing, it improves real-time collaboration efficiency, ultimately forming a new integrated smart safety management model of "intelligent perception, autonomous early warning, collaborative control, and continuous optimization."

VII. CONCLUSION

The construction of digital twins and intelligent perception systems is a key practice for Yulin Energy Chemical to promote the transformation of safety management towards intelligence and collaboration, mirroring the precision required in morphology monitoring under the guidance of its "Five Hearts" safety culture. This integration ensures the seamless coordination of complex industrial systems, providing a robust framework for the high-performance demands of technical manufacturing and distribution management. This system not only enhances the inherent safety level of enterprises but also provides a implementable and replicable "Chinese smart safety solution" for global clean coal technology projects, demonstrating the company's responsibility and innovative leadership in the context of the new generation of industrial internet.

AUTHOR CONTRIBUTIONS

Conceptualization –Jing Wang, Jie Cao, Zhaohui Huo, Junqi Hui and Zhiquan Wang; methodology – Jing Wang, Jie Cao, Zhaohui Huo, Junqi Hui and Zhiquan Wang; investigation – Jing Wang, Jie Cao, Zhaohui Huo, Junqi Hui and Zhiquan Wang; writing-original draft preparation – Jing Wang, Jie Cao, Zhaohui Huo, Junqi Hui and Zhiquan Wang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research received no external funding.

ACKNOWLEDGEMENTS

Not applicable.

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