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A Factory Management System Based on Digital Twin Platform and Methodology

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Abstract: Issues and current situation in digital twin platform construction are analyzed, and the factory management system based on such a platform, which includes production management module, control module, safety and environmental protection module, QHSE management module, and precision service module etc. is summarized in this paper. Real-time data interaction between virtual factories and physical factories enables continuous iterative optimization of this management system. It ensures uninterrupted production while achieving a comprehensive dynamic perception of factory operations, real-time optimization of production processes, automated production tasks, proactive trend prediction, efficient production control coordination, objective and precise management, and quantifiable decision-making support. This system significantly contributes to enhancing enterprise safety, environmental protection, quality improvement, cost reduction, and efficiency.

1. Current Situation Analysis and Issues

In recent years, with the swift advancement of emerging information technologies including the Internet, the Internet of Things (IoT), cloud computing, and big data, there has been a profound transformation in the manufacturing industry's landscape. In response to these technological shifts, Germany introduced the concept of Industry 4.0 during the Hannover Messe in 2011. Subsequently, Germany has elevated the policy of bolstering its manufacturing sector through the principles of Industry 4.0 to the level of a national strategy. Concurrently, nations such as the United States, the United Kingdom, France, and Japan have each introduced strategic plans for the upgrading of their manufacturing industries, customizing these strategies to align with the unique characteristics of their respective industrial manufacturing sectors.

In 2015, China unveiled the "Made in China 2025" initiative, known as China's own version of "Industry 4.0", which articulated a strategy aimed at transforming China into a manufacturing powerhouse. In line with this strategic objective, the plan specified nine strategic tasks and identified key areas for development within the framework of the "Made in China 2025" blueprint. Unlike the manufacturing strategies of other nations, "Made in China 2025" is tailored to the specific conditions of China's industrial sector. It places a special emphasis on the synergy between informatization and industrialization to spearhead and stimulate the overall advancement of the manufacturing industry. Additionally, the strategy prioritizes smart manufacturing and smart factories as the main direction for strategic development.

1.1 Current Status of Foreign Smart Factories

In recent years, the United States, England, Germany, France, and other countries have successively published "National Strategic Plan for Advanced Manufacturing", "Germany Industry 4.0 Strategy", "UK Industry 2050 Strategy", and "New Industrial Strategy for France". Among the emerging economies, India has published "Made in India", and South Korea has formulated "Future Growth Power Plan". Following the international financial crisis, nations across the globe have unanimously prioritized the manufacturing sector as the cornerstone of economic growth, propelling smart manufacturing to the forefront of their development agendas.

1.2 Current Status of Domestic Smart Factories

"Made in China 2025" outlines a strategic objective: "to strive to become a global manufacturing powerhouse within a decade." The detailed plan for the deep integration of informatization and industrialization specifies that the overarching action goal is to address the needs of smart manufacturing in vital sectors of the national economy. This involves innovating in smart manufacturing equipment and enhancing the systematic integration of major complete equipment and production lines to augment efficiency and competitiveness.

The "Development Plan for Smart Manufacturing (2016-2020)" puts forward that smart manufacturing is a new production method based on deep integration of new information and communication technology and advanced manufacturing technology, which covers all the manufacturing activities such as design, production, management, and service. It performs self-perception, self-learning, self-decision-making, self-enforcing, and self-adaptation.

1.3 Trends in Information Technology in the Petrochemical Industry

Information technology plays a crucial role in daily operation and management of modern petrochemical enterprises. To match up to their business models, international petrochemical enterprises usually refer to the standard ISA95 for informatization and adopt a three-layer architecture composed of the process control layer, production management layer and operation management layer to meet the needs at each business level and realize their control objectives in terms of effectiveness, safety, efficiency, energy consumption and environment.

2. Overall Design of the Factory Management System Based on Digital Twin Platform

2.1 Design Concept

The top-level design of a smart factory fully integrates the characteristics of the existing factory management mode and business processes to construct a unified architecture that is stable, integrated, compatible, expandable, and scalable.

2.2 Technical Architecture

The modular-developed and cloud-deployed design depends on microservices and component-based development technology, which helps integrate the application development and operation. Once a module is worked out, it is put into service, thereby improving the efficiency of application development.

The technical architecture of a smart factory consists of information acquisition layer, information transmission layer, information storage layer, platform layer, information application layer, standard specification system and information security system.

2.3 Application Architecture

This scheme mainly aims to complete the construction in aspects of digital handover and data standardization, production and operation optimization function, business management, intelligent innovation function, and data visualization as well. Data integration, application integration, and business integration are realized through the factory management system.

2.4 Functional Architecture

This scheme refers to the experience of smart factory construction in petrochemical and coal chemical industries, and abides by PetroChina's principles for the top-level design of smart oil and gas fields. In the scheme, data and business integration is achieved by the factory management system based on digital twin platform. Functional modules such as dynamic simulation, advanced control, production execution management, alarm management, patrol inspection management, equipment lifecycle management, OA, business management, and QHSE management are set up in the factory management system.

2.5 Data Architecture

The smart factory employs two modes for data acquisition: the Internet of Things (IoT) mode and standardized mode. Data related to design, procurement, and construction processes, as well as results, are systematically gathered and integrated into the dynamic database of the construction site. Meanwhile, real-time production data and video feeds are captured via IoT and fed into the factory's dynamic database. This dynamic database then delivers data services to smart applications through the smart production management platform. The data produced by these smart applications is subsequently archived back into the dynamic database for centralized management [1].

In terms of data receiving, the data of the factory dynamic database comes from the data of construction period and production period that are extracted by the data extraction tool covering the entire industry chain. The receiving adapter registers the metadata of the extracted data, including the source information and structure information of the data.

In terms of data storage, the incoming data are initially cached in their original format and subsequently transformed and processed in accordance with international standards. Once converted, the data are moved to a standard storage area, where they assume a stable data structure. Depending on business needs, data can be organized into thematic storage or undergo customized storage solutions.

In terms of data delivery, services for standard data, customized data, and result retrieval are offered. It is technically based on the service gateway approach, which enables registration and exposure of interfaces in the service directory via standard Restful API.

In terms of business applications, smart factory applications interact with data services within the system through a data service gateway provided by the dynamic database [2].

2.6 Deployment Architecture

An industrial isolation gateway is designed between production network and office network, and a firewall is designed for the office network. Because the video streaming data cannot pass through the industrial isolation gateway, a dedicated line protected by a firewall is independently deployed between the production network and the office network.

3. Application Scenarios of the Factory Management System Based on Digital Twin Platform

3.1 Production Control

(1) Smart inspection

The system automatically prompts the inspection personnel as per RFID of inspection terminals and inspection points, reminding them of the content and requirements for each inspection point, and recording the inspection results. Any problems discovered during inspection can be reported without delay via on-site pictures or videos through ex-proof inspection terminal handhelds. It helps to know the overall operation status of equipment, as well as standardize inspection task management, improve risk prevention, and reduce employee workload.

(2) Laboratory analysis

For items that require manual sampling and testing, such as water samples, exported product quality, etc., an online analyzer is designed to conduct automatic testing and analysis, thereby reducing the workload of manually recording and analyzing data.

(3) Equipment status monitoring

The process is to dynamically analyze real-time parameters and operating status of equipment, compare change curves, analyze change trends, predict various defects and faults of equipment in advance, and timely predict hidden danger problems. By doing so, this approach enhances the overall level of equipment management and safety oversight within the factory.

(4) Smart blind plate management

The platform can quickly generate a blind plate scheme based on 3D models before inspection and maintenance. The system automatically determines the position, connection method, size, and other information of the blind plates that need to be added, and automatically adds blind plate labels on the 3D model. It generates a blind plate ledger covering the whole field or any locations, standardizes the unified management of fixed and dynamic blind plates on site, fastens blind plate scheme preparation, and assures the functions such as quickly generating blind plate schemes, on-site job management, and automatic maintenance of blind plate ledgers.

(5) Warehouse management

Material QR codes are used to identify the types and storage places of materials, thereby enabling accurate query of out-put and in-put of warehouse and rapid positioning, and automatically generating inventory reports for materials.

It identifies equipment and corresponding spare parts, displaying their real-time status. This method facilitates systematic management of spare parts across various aspects, including inventory strategy, consumption and requisition, procurement initiation, and cost allocation, etc. It solves issues such as backlogs or shortages of spare parts, and achieves efficient and convenient warehouse management and real time sharing of warehouse information.

Equipment spare parts inventory and usage data are linked to the equipment management platform, allowing for timely updates of equipment data.

(6) Production control

Production scheduling daily report management: It is necessary to produce a daily production scheduling report. If this report is manually created by employees every day, there are difficulties such as diverse data sources, multi-level data referencing, and complex data calculations, leading to a heavy workload for employees and making it difficult to ensure the timeliness and accuracy of the report.

Production operation management: The system organizes various already-integrated safety-related monitoring systems to create a unified list for managing safety data. It can also display information that needs to be brought to the attention of dispatch personnel in a floating window on the graphical user interface.

(7) On-site operation management

Shift management: Based on the personnel shift change template, the system provides a function of entering personnel shift information and creating an overview of the data for handover. It also offers features such as viewing and exporting historical shift change records.

Production operation change management primarily facilitates document management. Users can upload electronic versions of records related to manufacturing processes into the system. In turn, the system offers functionalities to display, download, upload, and search for process documentation using keywords.

(8) Process technology management

Develop a database dedicated to process technology, encompassing data pertinent to process management and process documentation. This aims to efficiently manage and securely store both process flow data and process information data. It provides operators with document management, operation card management, and form management based on various types of data. Additionally, it uses 3D model simulations to display operational procedures and precautions for various processes.

3.2 Operational Optimization

By expanding the comprehensive perception of sensors, comprehensive sensing of multi-source equipment, work environment, personnel, and material inventory data is achieved. This allows for the real-time display of the operational status, modes, and trends of devices, thereby enhancing all-around and full-process monitoring of hazardous processes. Data analysis algorithms are deployed at key devices and critical nodes, and an intelligent control engine is integrated into edge controllers to automatically adjust and optimize the process based on the operational data trends. This enhances the stability and safety of device operation, ensures the uniformity of product quality, improves the yield of target products, reduces operational costs, and increases overall efficiency.

3.3 Energy Management and Control

The system conducts online acquisition, calculation, analysis, and processing of enterprise's energy data (including water, electricity, gas, wind, and heat, etc.), and dynamically displays statistical reports on energy management, balance analyses, and predictive analysis results. This facilitates the enterprise's energy and material balance, optimizes scheduling, and improves the operation and management of energy equipment. It also prevents production safety accidents that could arise from failures in utility engineering, thereby enhancing the overall level of energy management and safety in production [3].

3.4 Management and Control of Safety and Environmental Protection

(1) Work safety management

Special operations such as hot work, confined space work, and temporary electrical work are itemized, digitized, and proceduralized in terms of approval and permit conditions. Permit-approving personnel verify on-site conditions by referring to a checklist, and upload attachments such as on-site inspection photos. Only when all the working conditions are met, can the work permit be issued. The entire process of the operation is managed through information technology, enabling traceability and process management. This ensures that the application, review, permission, supervision, and acceptance of special operations are managed in an informational, standardized, and procedural manner.

The work permit management system can be extended to include routine operations such as the starting and stopping of machinery and pumps. By implementing risk identification and preventive measures, it ensures that every dynamic operation is carried out with proper planning, authorization, and process monitoring. This strengthens the control over hazardous operations, making the entire process managed informatively and standardized, and enhancing the level of safety management.

(2) Fire emergency management

By fully empowering chemical enterprises through the industrial internet, all four stages of emergency management, i.e., prevention, preparedness, response, and recovery, are covered. Utilizing VR and AI technologies, the system achieves precise delivery of emergency assistance materials, real-time updates of emergency resources, intelligent decision-making for emergency rescue, rapid coordination of emergency teams, and comprehensive recording of the emergency process. This improves the emergency rescue and response capabilities at all positions and throughout the entire plant, reduces the risk associated with on-site emergency drills, and perfects the emergency rescue and response procedures.

(3) Equipment integrity management and predictive maintenance

Based on a database of failure cases from similar equipment, including compressors, and an expert knowledge base, establish an equipment anomaly warning model. Utilize AI and self-healing technologies to establish an equipment operational status monitoring system, alongside a remote diagnostic and early warning center. This system can assess the health status and predicting failure trends for large units, key pumps, pressure vessels, and atmospheric critical containers. It enables early warnings for abnormal operating conditions and failure risks, such as severe unit vibration, rotational imbalance stall, tank leakage, pipeline corrosion, and bearing damage. This approach shifts maintenance from traditional reactive, periodic, and preventive strategies to predictive maintenance. It helps to avoid production losses due to downtime, excessive inspection and repairs, surplus spare parts inventory, and over-reliance on personal experience. By doing so, it effectively reduces equipment failures, mitigates accidents caused by equipment malfunctions, and ensures the safe, reliable, and extended operation of equipment throughout its service life.

(4) Management of major hazard sources

The management strategy for major hazard sources includes monitoring key parameters such as temperature, liquid level, pressure, concentration of combustible gases and toxic gases, composition, and flow rate, as well as intelligent video analysis information, interlock commissioning status, and integrated data management of energy (water, electricity, gas, wind, and heat, etc.). Such data are combined with the surrounding geographical and meteorological conditions, population distribution, and historical accident information to establish a comprehensive safety risk early warning model for major hazard sources, achieving comprehensive monitoring and precise early warning of safety risks. By strengthening the management of major hazard sources, safety risk monitoring and early warning are improved, thereby enhancing the safety management.

3.5 Decision Support

(1) Intelligent analysis of industrial video surveillance

Ensure comprehensive coverage of industrial video surveillance and augment surveillance in areas lacking on-site coverage.

Link on-site cameras with existing DCS, FA, FGS systems to achieve an alarm-triggered linkage with surrounding cameras.

Automatic monitoring, intelligent analysis, and timely warning of the operational environment and abnormal states are allowed by intelligent analysis of industrial video images combined with fixed and mobile monitoring devices. It focuses on covering smoke, flames, blind spots of gas sensors, perimeters of installations, high points of installations, and areas difficult to reach during inspections, and ensures operation under extreme weather conditions, accidents, disasters, and other special circumstances, to achieve panoramic, all-weather surveillance, strengthen monitoring of the production site, and prevent abnormal states.

(2) Management of unsafe personnel behavior

The number of personnel in the production area, along with their positions and identity qualifications, are authenticated and subjected to continuous monitoring.

Unsafe behaviors of various personnel, such as leaving post, sleeping on duty, and entering hazardous areas, are identified, and subjected to continuous monitoring and controlling. Prevent unauthorized activities, including rule violations, misoperations, and unauthorized actions by personnel.

(3) Enclosed management

The use of "video surveillance + AI" algorithms enables the identification of individuals and vehicles, as well as the monitoring and tallying of their entries and exits. Intrusion and emergency alarm systems, video surveillance systems, and personnel positioning systems are integrated for unified management with capabilities for regional segmentation and hierarchical control. This integration facilitates the display of monitoring point locations on electronic maps and allows for the real-time presentation of data, statuses, and surveillance footage for each monitoring point. Linkage of intrusion and emergency alarm systems, video surveillance systems, access control systems, personnel and vehicle information management systems, online visitor management systems, and personnel positioning systems, etc. enables to record, track, and display personnel and vehicle movements according to a timeline, and automatically retrieve video surveillance records.

(4) Circulation management

Establish an all-encompassing information management and monitoring system across every phase – production, storage, usage, operation, and transportation – to guarantee the traceability of hazardous chemicals from origin to destination and their real-time status, thereby rendering them fully traceable and controllable.

(5) Contractor management

The contractor performance evaluation index system should be established, and a comprehensive contractor management information system should be developed considering the contractor's qualification level, comparable historical performance, previous project execution record, safety management proficiency, project assignment personnel quality and other factors. This system enables the dynamic management of the entire process, including contractors' prequalification, tender management, selection, contracting, safety training and assessment, supervision over the operation process, performance evaluation, and decisions on contract renewal or termination.

The contractor management information system reserves interfaces to push information about contractors involved in production safety accidents or having significant construction quality hazards, along with information of their management and technical staff, to similar enterprises. This gradually implements a dynamic disqualification system for unqualified contractors, thereby improving the service capabilities of contractors.

(6) Training management

Leverage Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and Digital Twin technologies to deliver online, panoramic, and immersive training experiences to all employees. Customize training and assessment materials to align with the precise roles and responsibilities of each employee, considering their individual educational backgrounds, professional experiences, and any specialized operational certifications they possess. Through an automatic scoring and reward-penalty mechanism, foster a proactive learning attitude among all employees, thereby enhancing the safety capabilities across the entire industry [4].

(7) Collaborative office work

Employing IT-enabled (networked) collaborative tools allows for full-process management of personnel, facilitating remote approvals, progress control, and progressively realizing paperless office work for personnel and training management.

4. Summary

By digitization, information technology is integrated into the entire production process in five key areas: safety, environmental protection, quality improvement, cost reduction, and efficiency enhancement. Data integration and software integration technologies are employed to comprehensively process both the static data delivered digitally and the dynamic data from production operations after project commissioning, facilitating the advancement of production management and operational control technologies towards informatization, digitization, and intelligence. The deep integration of factories with the industrial internet brings about digital management of safe production, networked collaboration, and intelligent control.

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