Development and Analysis of a Petrochemical Smart Factory Utilizing Digital Twin Technology

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Abstract: Digital twins are increasingly recognized as a pivotal technology in implementing strategies for smart manufacturing and the industrial internet, bridging the gap between the information and physical worlds. This growing interest is evident in both academic and industry circles, with the development and application of digital twins becoming a topic of significant focus. This article commences by providing a comprehensive definition and exploring the unique characteristics of digital twin technology in the context of smart petrochemical factories. It then delves into the proposed overall architecture of such systems, highlighting their potential to revolutionize industry practices. The paper culminates by detailing the main six aspects and thirteen key tasks essential for the successful implementation of digital twin technology in petrochemical factories. These encompass various stages from initial concept to practical deployment, offering a roadmap for future advancements in this field.

K**ey words**: Digital twin; smart factory; petrochemical factory

Over a decade, digital twin theory has matured, with varying interpretations from standardization bodies, academia, and industry. At the same time, due to the development of new generation information technologies such as cloud computing, the internet of things, big data, and artificial intelligence, the realization of digital twins has gradually become possible. The concept of digital twins was proposed by Professor Grieves of the University of Michigan in the United States in 2003 as a "virtual digital expression equivalent to physical products" [1]. Subsequently, from 2003 to 2010, digital twins were referred to as the "mirrored spatial model" [2]. It was not until 2011 that NASA officially proposed the concept of "Digital Twin" in a technical report [3-4], And defined as "a system or aircraft simulation process that integrates multiple physical quantities, scales, and probabilities". In the following years, more and more research will apply digital twins to the aerospace field, including fuselage design and maintenance, aircraft capability assessment, and aircraft fault prediction [5-6].

After more than 10 years of development, the theory of digital twins has been continuously improved, with different definitions and understandings given by standardization organizations, academia, and industry [7-9]. NASA believes that digital twinning is a multi-physical, multi-scale probabilistic simulation of aircraft or system integration, which uses the best available physical models, updated sensor data, and historical flight data to reflect the true characteristics of the entire lifecycle of the flight entity corresponding to the model [3-4]. Tao Fei defines digital twinning as a technical means of using historical data, real-time data, and algorithmic models to create virtual entities of physical entities in a digital manner, simulating, validating, predicting, and controlling the entire lifecycle process of physical entities [10-11]. In recent years, digital twins have gradually been extended and applied to industries such as energy, cities, agriculture, shipbuilding, manufacturing, healthcare, and environmental protection [12-18]. In the field of smart manufacturing, digital twins are considered an effective means of integrating information and physical worlds [19-20].

China's petrochemical industry, a global leader in scale, embarked on its informatization journey in the 1990s, and has gone through five stages of development: "starting and technology introduction", "decentralized construction", "unified planning and construction", "deepening application, centralized integration", and "integration sharing, collaborative innovation". The production and capacity have been significantly improved, and the industrial scale has ranked among the top petrochemical countries in the world [21]. However, compared to high-quality development, it still faces problems such as low resource and energy utilization rates, low high-end manufacturing levels, and late start of information construction [22-23] (smart factories have not published articles). At the same time, the petrochemical manufacturing process has characteristics such as nonlinearity, multivariability, strong coupling, large lag, multi-objective, and multiple constraints, making it extremely difficult to achieve continuous stability in its production process [25-27]. New technologies and models are needed to address the new challenges of safety, environmental protection control, and green and low-carbon development. The petrochemical industry urgently needs to be empowered by digital twin technology to deeply integrate innovative process technologies with the new generation of information and communication technology (ICT), and achieve sustainable and high-quality development.

At present, the application of digital twins in the petrochemical industry is insufficient, and a complete case has not yet been formed, especially for the digital twin solutions in the petrochemical field, which are almost blank. Therefore, in order to achieve the practical application of digital twin technology and promote the high-quality development of the petrochemical industry, this article provides a detailed explanation of the definition and connotation of the new generation of petrochemical digital twin smart factories, and proposes the overall architecture, key technologies, and key construction contents.

1. A digital twin smart petrochemical factory.

1.1 definition

Petrochemical smart factory is a new manufacturing model oriented towards the petrochemical industry, covering the entire industrial chain of petrochemical production. It deeply integrates the new generation of information and communication technology with the resources, processes, equipment, environment, and human manufacturing activities of the petrochemical production process, enhancing the four key capabilities of comprehensive perception, prediction and warning, collaborative optimization, and scientific decision-making, and improving the level of factory operation and management in a more refined and flexible manner, And promote the formation of new manufacturing and business model innovation [25, 28-29].

Driven by the new generation of information and communication technology and petrochemical manufacturing technology, the digital twin smart petrochemical factory is built on the industrial internet platform through the software encapsulation of complete technology, digital delivery of engineering construction, and combined with mixed modeling and correction of industrial data. Driven by data and models, it improves the efficient utilization of resources, production control optimization, and reliable operation of equipment smart operation level such as safety, environmental protection, and low-carbon.

1.2 characteristic

The digital twin smart petrochemical factory has four characteristics: automation, platform based, integration, and digital twinning.

1. Automation

Industrial automation is the foundation. It includes three levels: firstly, process control automation, such as DCS, PLC, SIS, as well as PID self-tuning, advanced control (APC), automatic interlocking control, automatic switching, one key operation, etc; The second is equipment automation, such as three-dimensional warehouses, track robots, and special operation robots; The third is procedural automation, such as low code application platforms (LCAPs), robot process automation (RPA), knowledge automation (KA), etc.

2. Platform based

Platformization is the support. This refers to the petrochemical industrial internet platform. The edge cloud platform on the enterprise side is the "edge and end" in the "cloud, edge, and end" of the group's petrochemical smart cloud, which is the extension and sinking of various cloud capabilities of central cloud. Collaborate with headquarters cloud to form a petrochemical industrial internet platform with unified architecture, shared services, and data exchange.

3. Integration

Integration is the core. Comprehensive integration of different IT systems and production facilities within the enterprise aims to establish a highly integrated system. It can be understood as three levels: the in-depth application of information systems such as ERP/PLM/MES/SCADA within the enterprise and the deep integration between systems; By networking devices, various digital devices can be built into a centralized and controlled equipment network management system; The information system and device layer have functions such as command issuance, status feedback, and dynamic adjustment, reflecting the deep integration between information planning and physical devices.

4. Digital twinning

Digital twins are means. It is the process of establishing a digital model for physical entities, digital entities, and other entities or entity combinations that can have a digital model. The measurement standards for this process are Fidelity and Credibility, which manifest from similarity in form, simulation, and spirit (including static and dynamic) to difficulty in distinguishing true from false. By using virtual to real, virtual to real interaction, and virtual control, the level of digital twin biochemistry is reflected. In the construction of petrochemical smart factories, digital twins such as equipment level, unit/device level, factory level, and enterprise level are constructed to achieve service applications such as description, diagnosis, prediction, and optimization.

2. Overall structure and key technologies

2.1 Overall structure

The overall structure of digital twin smart petrochemical factory can be divided into three levels: physical space, interaction layer, and twin space. The physical space is a physical petrochemical factory, which is the foundation of the twin factory. Comprehensive perception and precise control of the physical factory are the prerequisites for establishing a digital twin smart factory; the interaction layer supports the connection and mapping between physical space and digital space, achieving the collection, transmission, and edge control of IoT data; digital space is the description and characterization of physical entities from multiple dimensions, spatial scales, and temporal scales.

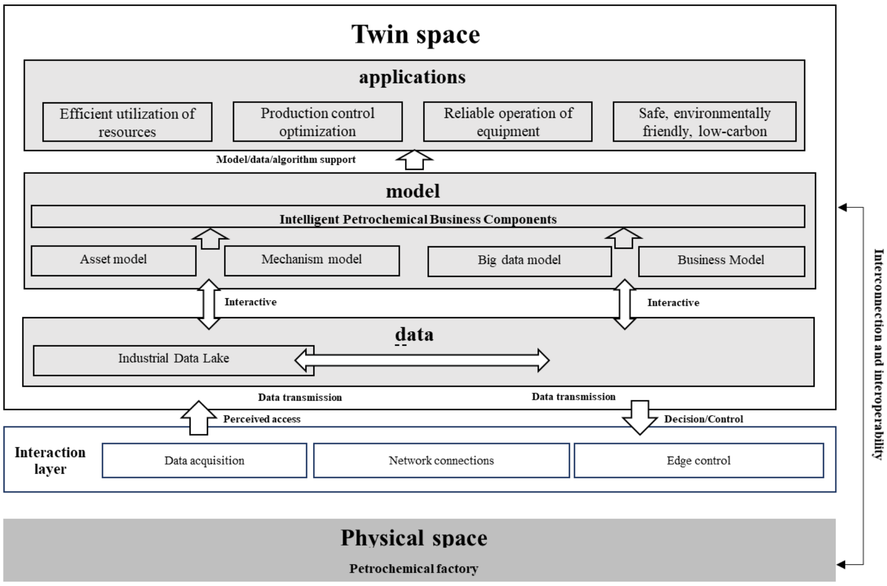

Fig.1 Architecture of digital twin smart petrochemical factory

2.2 key technologies

- Digital twin industrial data

Through the collection of industrial data at the interaction layer and corresponding data governance work, industrial data is stored in the industrial data lake, and industrial applications are supported through data analysis and data services. Industrial data collection includes the collection and governance of unstructured data such as industrial production time series data, structured management process data and device design documents, industrial site audio and video, exploration and development volume data, geographic information data, etc. The Industrial Data Lake utilizes the technology of big data distributed storage to organically combine industrial models, industrial IoT, real-time optimization, and other capabilities at the data level, constructing temporal data storage, structured data storage, and unstructured data storage that can scale linearly in both performance and capacity. Industrial data analysis includes basic data computing technology and big data analysis services, among which basic data computing technology includes parallel computing technology, stream computing technology, and data science computing technology. Industrial data services are services that utilize industrial big data technology to provide applications with data reading, analysis, calculation, storage, and other services in a service-oriented manner, including data access services and data analysis services.

- Digital twin industrial model

The digital twin industrial model includes asset model, mechanism model, big data model, business model, and multi model fusion of these four types of models. Describe the physical assets of the factory through an asset model, describe the production reaction and operation process through a process mechanism model, describe the statistical patterns of factory data through a big data model, and encapsulate industry rules, experiences, and cases through a business model.

After the model construction is completed, it is necessary to create a more complete digital twin through the "splicing" of multiple types of models. Through multi model fusion technology, asset models, mechanism models, big data models, and business models are correlated and integrated. Model fusion technology includes cross disciplinary model fusion technology, cross domain model fusion technology, and cross scale model fusion technology

● Digital twin industrial model

Based on data and models, through multidisciplinary coupling applications, precise mapping of petrochemical factories in physical space to industrial models in twin space is achieved. Through bidirectional interaction feedback and iterative operation of the two, the state of physical petrochemical factories is synchronously presented in twin space. Through diagnosis, analysis, and prediction of industrial models, decision-making and control behavior of petrochemical factories in physical space is optimized. Specific applications include efficient resource utilization Four aspects: optimization of production control, reliable operation of equipment, safety, environmental protection, and low-carbon.

3. Key construction content.

The construction of digital twin smart factories focuses on 13 key tasks in six aspects: research and development design, engineering construction, production and operation, business management, edge cloud platforms, smart equipment and technology, as shown in Figure 2.

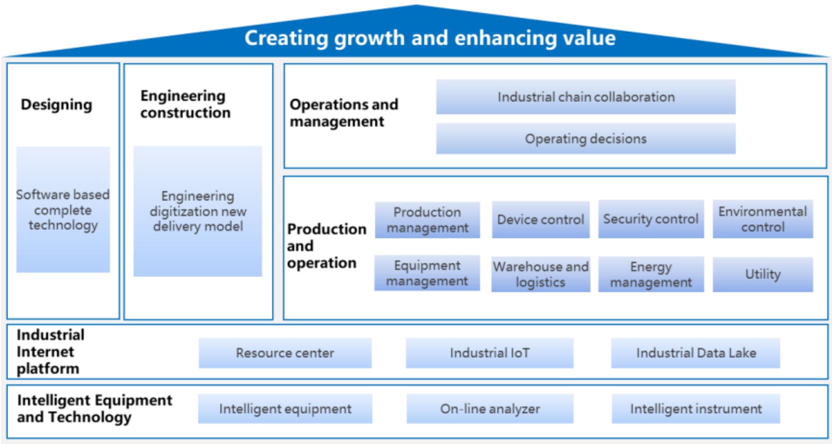

Fig.2 Key construction content of petrochemical digital twin smart factory

1) Content 1: Implement collaborative optimization of production plan scheduling

In terms of production planning, with the goal of maximizing economic benefits and based on an smart operation optimization model driven by real-time data, through regional collaboration, plan optimization, and scheduling optimization, market demand forecasting, plan scheduling, and inventory management are connected to achieve integrated optimization of production plan adjustment, dynamically respond to market changes, calculate production benefits, and achieve business finance integration.

2) Content 2: Implementing smart coordinated control of devices

In terms of device control, based on mechanism models, big data models, and hybrid models, conventional control, advanced control (APC), real-time optimization (RTO), smart control and other technologies are adopted to improve the production and operation control level of refining and fine chemical factories, meeting the production needs of enterprises for safety production, smooth operation, optimization and efficiency, Realize smart coordinated control of the entire production process in refining enterprises.

3) Content 2: Implementing smart and unmanned production execution

In terms of device operation, technologies such as robots, machine vision, the Internet of Things, AR/VR, etc. should be utilized to comprehensively improve the unmanned and smart level of production control in terms of operation management, scheduling management, laboratory management, operation training, etc., to meet the requirements of enterprise safety production, stable operation, and efficient control, extend the maintenance cycle of enterprises, improve product quality, and improve economic benefits, Realize the overall smart control of enterprise production control business.

4) Content 4: Implementing predictive maintenance for equipment failures

In terms of equipment management, it is necessary to establish a lifecycle management system that runs through the operation, maintenance, renovation, and scrapping of equipment assets, to achieve equipment status monitoring, health assessment, fault diagnosis, and predictive maintenance, and to achieve stable and optimal equipment operation.

5) Content 5: Achieving sustained reliability and energy-saving optimization of energy media

In terms of energy management and public engineering, it is necessary to carry out refined management and online optimization of the entire process of energy supply, production, transportation, conversion, and consumption, comprehensively coordinate the use of energy media such as water, electricity, steam, and wind, monitor and optimize the operation status of various energy-saving facilities, achieve multi medium energy optimization and energy cascade utilization, and achieve "maximum energy efficiency, visualized energy flow, and online optimization".

6) Content 6: Implement risk source control

In terms of production safety management, it is necessary to combine the HSE management system, use new generation information technologies such as industrial Internet, big data, 5G, AI, etc., and enhance the perception, monitoring, early warning, disposal, and evaluation capabilities of petrochemical industry safety production through information and smart means in hazard identification, hazard prediction, and emergency response, to achieve pre prevention and rapid disposal of emergencies.

7) Content 7: Realizing collaborative optimization of environmental protection and production

In terms of environmental management, it is necessary to establish an smart monitoring and control system for environmental emissions, achieve full process management, visual monitoring, smart analysis and traceability of wastewater, exhaust gas, and solid waste from the source, process to end of production equipment and storage and transportation systems, establish big data analysis models, predict production emissions, automatically provide production optimization plans and execute them.

8) Internal: 8: Realize unmanned and smart logistics links

In terms of warehousing and logistics, it is necessary to establish an agile supply chain driven by customer demand, enhance the safety, stability, and smoothness of the logistics links in the supply chain, improve the intelligence level of key logistics links such as transportation, warehousing, and handling within the factory, realize the value added of logistics, promote cost reduction and efficiency improvement, smooth supply and demand, and industrial upgrading.

9) Content 9: Achieving collaborative manufacturing of upstream and downstream integration in the industrial chain

In terms of industrial chain, we should focus on modernizing the industrial chain, promote the linkage and coordination of upstream and downstream enterprises, and support the optimization and allocation of resources for park type and base type petrochemical enterprises. Promote the linkage and coordination of upstream and downstream enterprises, achieve online release, automatic matching, and offline docking of bulk raw material and product information of upstream and downstream enterprises.

10) Content 10: Implementing smart decision-making based on artificial intelligence

In terms of business management, advanced artificial intelligence technologies such as NLP, speech recognition, and data intelligence should be used, combined with a large amount of unstructured data such as text and voice accumulated in areas such as big supervision, risk control, bidding, and customer service. Data mining and smart analysis of voice should be carried out to achieve value leadership, scientific decision-making, risk control, efficient collaboration, drive business innovation and development, and improve corporate governance and risk prevention capabilities; Improve user satisfaction, reduce labor costs, enhance market competitiveness, and assist in the development of platform economy.

11) Content 11: Realizing the softening of autonomous petrochemical complete technology

In terms of research and development design, it is necessary to build a core database and key technology models based on petrochemical complete set technology, and package them with software to adapt to platform applications, forming four types of industrial applications: efficient resource utilization, production control optimization, reliable equipment operation, and safety, environmental protection, and low-carbon. Empowering the smart operation of factories, ensuring the efficient use of industrial technology and information security.

12) Content 12: Establishing a new digital delivery model

In terms of engineering construction, establish an information organization model with the factory object as the core, covering engineering design, procurement and construction, testing and commissioning, and other engineering stages, to achieve seamless, fast, and low-cost digital delivery, laying the foundation for the construction of smart factories for owners. Transforming from one-time result delivery to progressive delivery mode, leading by engineering companies to demand for smart factories, and expanding from fixed asset delivery to "fixed asset and intangible asset" delivery, establishing a new digital delivery model and creating a data twin foundation for smart factories.

13) Content 13: Building an edge cloud platform for cloud edge collaboration

In terms of platform support, it is necessary to build an edge cloud platform that utilizes its low latency, self-organization, and definability to enhance enterprise IoT perception, data resource management, and industrial application capabilities. It should also collaborate with the headquarters central cloud in terms of applications, services, and resources to achieve digitalization of production and operation, and smart resource management.

14) Content 14: Improving the level of smart infrastructure

In terms of infrastructure, it is necessary to upgrade and transform smart instruments, special operation equipment, and network communication, create a digital production environment, and achieve rapid data collection, transmission, and remote control of equipment.

4. Conclusion and Prospect

This article expounds the definition and characteristics of digital twin smart petrochemical factory, then proposes the overall architecture, and finally points out the main 6 aspects and 13 key tasks to be finished.

At present, the above technical solution are undergoing technical breakthroughs and pilot applications in Sinopec's subsidiary enterprise Zhongke Refining and Chemical company, which is the largest refining and chemical integration enterprise newly built during the 13th Five-Year Plan period of Sinopec, including 10 million tons/year of oil refining, 800,000 tons/year of ethylene and its derivatives, 300,000-ton crude oil terminal, 4 sets of 450t/h high-pressure CFB boilers for combined heat and power generation, 3 sets of 100MW steam turbine generator units and other supporting utilities. Among them, the 800,000 tons/year ethylene factory adopts completely domestically-owned process technology. Based on the independently developed industrial Internet edge cloud platform, this solution constructs a digital twin of the ethylene factory with industrial software as the core, and carries out technical applications such as real-time optimization of the ethylene factory process, smart operation control of the ethylene factory, remote monitoring and optimization of three type important machine, risk prevention and control of the power supply system of the ethylene factory, and prediction of nitrogen oxide concentration in the ethylene factory. It is expected that the overall production efficiency of the ethylene factory can be increased by about 2%, NOx emissions can be reduced by more than 3%, waste alkali emissions can be reduced by 5%-10%, and energy consumption can be reduced by more than 2%.

To accelerate the development of petrochemical digital twin smart factory, it is necessary to promote the close integration of "government, industry, academia, research, and application". We should use the petrochemical industrial Internet platform as the support, strengthen and highlight the dominant position of technological innovation in enterprises, starting from market demand, with major industrial projects as the traction, and enterprises as the leading role, closely cooperating with scientific research institutions, design units, construction units, and software companies to accelerate the establishment of a technology innovation system with enterprises as the main body, market-oriented, and close integration of industry, academia, research, and application. At present, Sinopec has established the petrochemical smart cloud industrial Internet platform, and Petro-Cyber Works Information Technology company has built the petroleum and chemical industry Internet platform ProMACE. They will focus on the strategic goal of building a "one base, two wings, three new" industrial structure around Sinopec and creating a "world-leading clean energy chemical company", to help the transformation and upgrading and high-quality development of China's petrochemical industry.

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