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Strategic Research on the Goals, Characteristics, and Paths of Intelligentization of Process Manufacturing Industry for 2035

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Abstract: This study focuses on the constitutive characteristics, dissipative structure and process, modeling mechanism, and other physical essence related to the manufacturing processes in process manufacturing industries. The major research objects of the study are petrochemical and steel industries; intelligence was integrated with the concept of cyber-physical systems (CPS) to investigate the possible approaches for realizing self-sensing, self-learning, self-decision-making, self-execution, and self-adaptation of plant-wide dynamic processes, which include operation, management, and service. Here, the approaches for constructing a CPS-based intelligent factory were also investigated. Furthermore, goals, characteristics, and paths were proposed for the intelligent development of the process manufacturing industry toward 2035.Countermeasures and suggestions regarding mechanism construction, science and technology projects, financial support, technology R&D, intellectual property, and international communication were also proposed.

Keywords: process manufacturing industry; intelligence; steel industry; petrochemical industry; 2035

1 Introduction

As the primary body of China’s real economy, manufacturing is an important part of the modern economic system and is mainly divided into process and discrete manufacturing. Process manufacturing includes industrial sectors, such as steel, petrochemicals, building materials, chemicals, and nonferrous metals. A production process cluster comprises related but different types of equipment. Typically, operations of process manufacturing industries are accompanied by physical and chemical changes, and a dynamic nonlinear coupling is another important characteristic. Owing to this complex mechanism, digitalizing and establishing mathematical models are difficult tasks. In addition, owing to complex raw materials and large fluctuations in production conditions, the technological parameters of related processes must be reset in real time. After decades of development, the process manufacturing technology in China has significantly improved, the overall strength of the industry has rapidly increased, and its international influence has remarkably enhanced. Currently, the process manufacturing technology of China has

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become the world's most complete and largest-scale process manufacturing system. However, unlike manufacturing industry in advanced countries, China's process manufacturing industry has the following problems: a low utilization ratio of resources and energy, unreasonable product structure, serious production capacity excess, lagging development of high-end manufacturing, and low safety and environmental protection requirements. In the future, the industry will encounter more severe challenges, such as resources, markets, environmental protection, and competition. Thus, it is crucial to accelerate the industry's transformation and upgrade and improve its quality and efficiency. Accelerating the development of greening and intelligentization has become critical for the process manufacturing industry of the country [1].The period from the current time to 2035 is key for the development of intelligent manufacturing in China. Its process manufacturing industry should seize this historic opportunity, concentrate on the strength of key breakthroughs, and realize intelligent manufacturing immediately to support the development of a high-quality economy.

Studies on intelligent manufacturing in China and internationally have focused mainly on the discrete manufacturing industry (e.g., Germany's Industry 4.0). However, the intelligentization of process manufacturing is different from discrete manufacturing. The theory and practice of process-based intelligent manufacturing are still in the exploration process, and no commonly accepted theoretical system or application case is available. This study focuses on physical ontology problems such as constitutive characteristics, dissipative structure and process, and modeling mechanism of the process manufacturing industry, as well as present goals, characteristics, and paths for the intelligentization of the process manufacturing industry in 2035. The goal is to provide a theoretical support for the innovative development of the process manufacturing industry in China.

2 Characteristics of a process-oriented intelligent manufacturing industry

The manufacturing processes of different industries have both common and individual characteristics. By examining these characteristics, intrinsic physical essence of a dynamic operation and the basic characteristics of intelligentization development become clearer.

2.1 Common characteristics

A process manufacturing operation is created by the nested combination of processes at the atomic/molecular, sector/equipment, and process/factory levels. It is constructed through the integrated mechanisms of nonlinear interaction–dynamic coupling, networking, and structural integration. The importance of the process manufacturing operation is the overall flow and transformation, which embodies the combination of holistic thinking and reductionism and is guided by holistic integrated thinking [2]. Process manufacturing comprises heterogeneous processes that exist as non-detachable integrated operations and is suitable for continuous and mass production, which is a common feature of manufacturing. For example, the production process in manufacturing plants is continuous or quasi-continuous, and the elements of a dynamic operation include "flow," "process network," and "operation program" [3,4].

2.2 Individual characteristics

Differences exist in the production processes of various industries, and the objects being processing objects also vary; therefore, these processes have their own individual characteristics. For example, various industries have different forms of "flow." Some manufacturing processes use mainly a "continuous flow" and are supplemented with an "intermittent flow," while others are the opposite. The phase compositions, physical characteristics, and working conditions of "flow" in different industries also vary [5]. For the process manufacturing industry, the flow/rheology and physicochemical changes in the material-energy flow occur in the time–space boundary. The mode of operation is complex, and the related processes are difficult to solve and digitize, resulting in different "information". Therefore, the information flow and network characteristics are different, and one should pay attention to the organic combination of digital and physical systems.

2.3 Physical essence of the dynamic operation process

The physical essence of the dynamic process manufacturing operation can be summarized as follows: material flow is driven by energy flow and operates dynamically and orderly along a specific "process network" according to the set of "procedures," achieving a multi-objective optimization. The components of the material flow in different industries are different, and the composition of the energy flow also varies [6].However, different forms of "flow"

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all operate in the corresponding "process network" based on the set of "procedures." The dynamic operation of process manufacturing is characterized by openness and non-equilibrium, and it belongs to the dissipation process in a dissipative structure. To optimize the dissipation process, the process system's operation state should be dynamic–orderly and collaborative–continuous/quasi-continuous. The "order" that dominates the process structure and operation originates from the internal structure and related information of the manufacturing process. Further, the self-organization of the manufacturing process comes from the rational configuration and assembly of the function sequence and the spatial order and time sequence of the relevant process devices. The strength of the self-organization of the manufacturing process depends on the analysis–optimization of the process function, the cooperation–optimization of the interaction relationship, and the reconstruction–optimization of the process [2].

2.4 Basic characteristics of the process-oriented intelligent manufacturing industry

The core objective of intelligence in process manufacturing is to improve the flexibility in dealing with markets in the production and operation and to improve efficiency, safety, and cleanliness in the production process. To improve the economic efficiency of enterprises, a digital physical fusion system was developed. The corresponding characteristics include a physical information system with a material flow network, energy flow network, and information flow network, or "three networks fusion and coordination"; functions of comprehensive perception, intelligent decision-making, precise execution, and deep service; specific features such as self-perception, self-learning, self-decision making, self-executing, and self-adaptation. Other characteristics involve dynamic–precision design, collaborative–optimization operation, efficient integrated management, safety-low inventory supply chain, and differentiated services [5].

3 Goals for the intelligentization of the process manufacturing industry

As an important part of the manufacturing industry of China, the process manufacturing industry, which is represented by the iron and steel industry and the petrochemical industry, is not only the pillar industry of the country's economic and social development but also the cornerstone of the real economy. The output value of the process manufacturing accounts for approximately 47% of the industrial output value above designated size. Although the overall scale and comprehensive strength of the process manufacturing industry of the country have been significantly improved, certain gaps remain in its competitive advantage, technological capability, brand quality, and environmental friendliness when compared with advanced countries. The problem of the structural imbalance between supply and demand is also more prominent.

Currently, breakthroughs continue to be made in the mobile Internet, big data, cloud computing, Internet of Things (IoT), Fifth-Generation mobile communication (5G), block chain, and other new-generation information technologies. In particular, the new generation of intelligent manufacturing technology, which is formed by deep integration of new-generation artificial intelligence (AI) and advanced manufacturing technologies, has become the core driving force of the new round of the industrial revolution. China's economy has shifted from a high-speed growth to a high-quality development stage, and this is in the key stage of changing its development mode, optimizing the economic structure, and changing the growth momentum. Hence, a new generation of AI or other major innovation are urgently needed to support this growth [7].

The report of the 19th National Congress of the Communist Party of China highlights that the development of an advanced manufacturing industry and the construction of a manufacturing power must be accelerated. Thus, promoting the intelligent development of the process manufacturing industry is an inevitable option to comply with the strategy of manufacturing power. It is also a crucial approach to adapt to the development of the digitalization, networking, and intelligentization of the process manufacturing industry in the new era to advance supply-side structural reforms and to support high-quality economic development.

The intelligent development of the process manufacturing industry should adopt the principles of "theoretical breakthroughs, standards leading, overall planning, top-level design, innovation-driven transformation and upgrading, pilot demonstration, and steady progress"; strengthen the structural reform of the supply side as the main line; advocate intelligent plants as the main direction; and promote the development of a deep integration of information and advanced manufacturing technologies. Thus, the intelligentization of technological development and engineering designs and intelligent production processes, operations and management, and supply chains and services should be promoted. Further, breakthroughs in the bottlenecks of key intelligent technology that restrict the process of "integration of informatization and industrialization" and the short board of major intelligent equipment must be encouraged. Modern and intelligent process manufacturing plants and operation modes should be constructed. We should also promote the transformation of quality, efficiency, and power in China's process manufacturing industry to achieve a significant transformation from a large to a strong development mode.

In 2025, digitalized and networked manufacturing and deep applications should be promoted in the key process manufacturing enterprises in China. In some areas, pilot and demonstration processes should be applied to intelligent chemical plants. The application scope should be further expanded if remarkable achievements are obtained allowing the country to enter the global advanced ranks of intelligent manufacturing in the process manufacturing industry. In the steel industry, China should establish intelligent steel plants covering different process structures and enter the world's advanced ranks in application technologies. The demonstration plant should realize a digital process design, intelligent production control, lean operation, and open system structure. Meanwhile, in the petrochemical industry, China should promote digitalized and networked intelligent plants; start the pilot demonstration of digitalized and networked intelligent plants; and enter the world's advanced ranks of intelligent manufacturing.

In 2035, the pilot demonstrations of the digitized and networked intelligent plants should be complete. The application begun to promote and accomplish the transformation and upgrade of the process manufacturing industry of China, ensure that some enterprises enter the world's leading ranks, and lay a solid foundation for the country to develop a world-class manufacturing power in 2050. For the steel industry, the intelligentization level of the entire industry should be fundamentally improved to reach the world's advanced level. Some enterprises should also achieve the world's highest level. In the petrochemical industry, digitalized and networked intelligent plants should be promoted and popularized. Moreover, the intelligent manufacturing industry should generally reach an advanced level, and some enterprises should achieve a world-class level.

4 Development ideas for the intelligentization of the process manufacturing industry

Intelligent plants are important contributors to realizing the intelligentization of the process manufacturing industry. To promote the intelligent development of the process manufacturing industry, intelligent plants are key aspects to judge and propose development ideas. This study presents development ideas for the intelligentization of steel and petrochemical plants.

4.1 Development ideas for the intelligentization of a steel plant

Steel enterprises should focus on the three aspects of product manufacturing, energy conversion, and waste disposal and recycling in the steel manufacturing process. Based on the synergy integration of the material flow network, energy flow network, and information flow network of the cyber–physics system, information technologies such as the IoT, big data, cloud computing, and AI should be integrated with the design, operation, management, and service of iron and steel manufacturing processes to build functions such as comprehensive perception, intelligent decision, precise execution, and deep service. These can optimize the steel manufacturing process structure, especially the dynamic operation structure, and ensure an improvement in intelligent control and management in the entire operation process.

4.1.1 Architecture of the cyber–physics system of a steel plant

From the physical mechanism perspective, the related system architecture (Fig. 1) [6] is characterized by that the manufacturing process control system includes the process control system (PCS) and "interface" technology, and that the production execution system (MES), energy management system (EMS), PCS, and enterprise resource planning system (ERP) are integrated. Among these systems, the foundation of the PCS technology, which is closely related to the "interface" technology, is relatively weak and should be one of the key entry points in the R&D of the system architecture.

4.1.2 Architecture of the intelligent manufacturing technology of a steel plant

Fig. 2 shows the intelligent manufacturing technology architecture of a steel plant. The data center, knowledge center, and digital twinning together constitute the support platform for the intelligent manufacturing steel plant. Optimizations of the sector, interface, and process become the physical foundations of intelligent manufacturing in steel plants. The processes of quality control, integrated planning and scheduling, and energy/environmental protection–production coordination are used as the command center of the entire process of the dynamic and orderly operations. Further, the supply chain global optimization and service lifecycle management provide a new profit model for the enterprise operation.

The application of intelligent steel plants should focus on the optimization of the material, energy, and information flow networks or the "three networks synergy." The following six fields should be integrated and optimized: digital

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engineering design, intelligent control of the entire process operation, overall process quality control, integrated planning and scheduling, energy/environmental protection and production coordination, and supply chain and service chain global optimization.

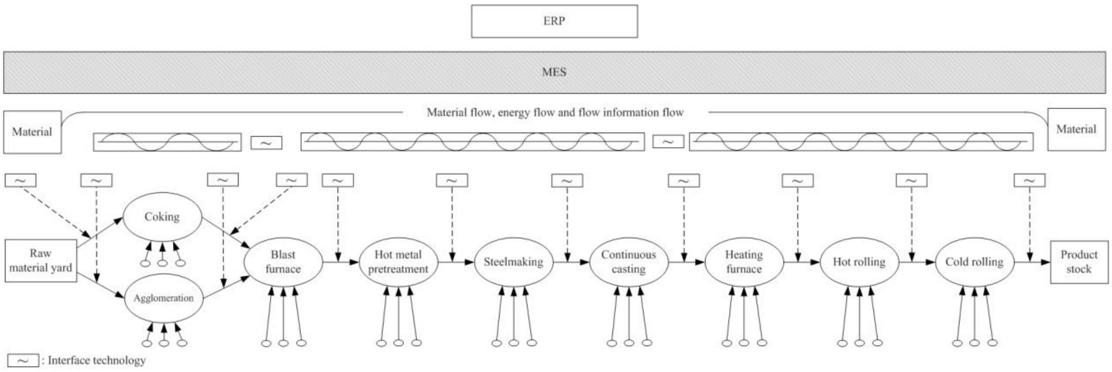

Fig. 1. Schematic of a cyber–physical system architecture in a steel plant.

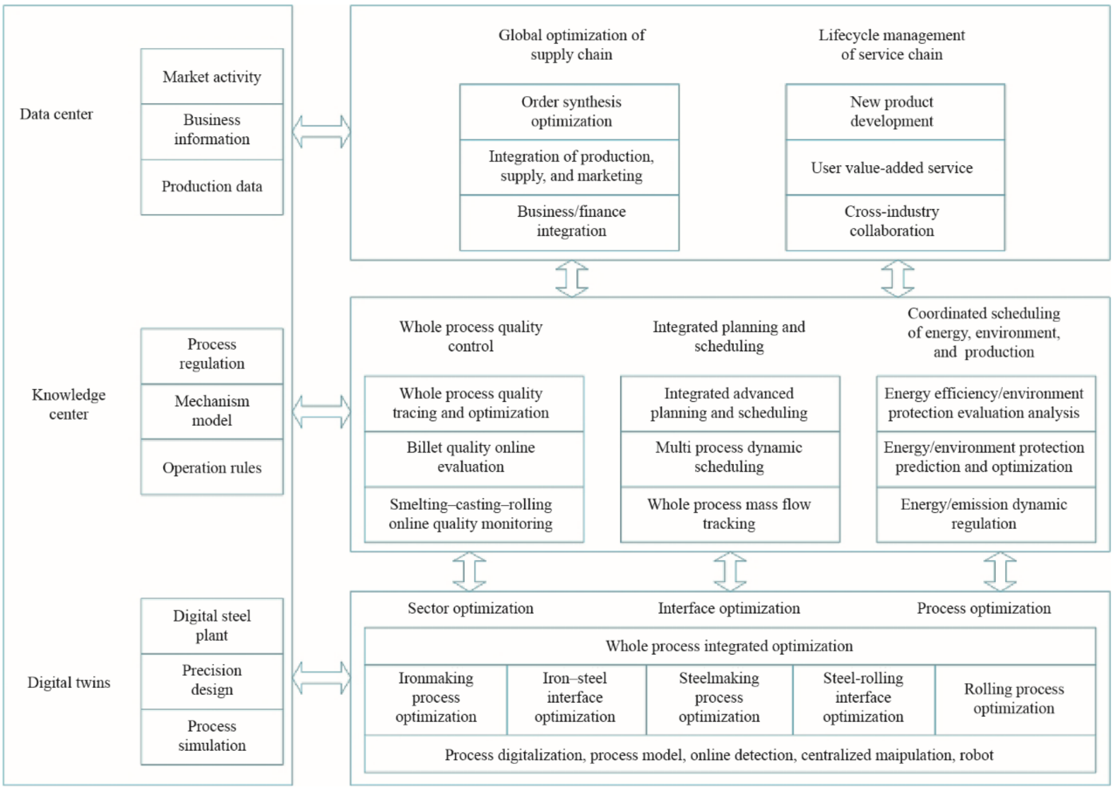

Fig. 2. Schematic of the technological architecture of an intelligent steel plant.

4.2 Development ideas for the intelligentization of a petrochemical plant

For all types of manufacturing models for the petrochemical industry, development ideas include the following: covering the entire industrial chain of petrochemical production; integrating the new generation of information technology with the resources, process, equipment, environment, and human manufacturing activities of the petrochemical production process; promoting horizontal, vertical, and end-to-end integration; establishing four key abilities: comprehensive perception, prediction and early warning, collaborative optimization, and intelligent decision making; improving the operation and management of petrochemical plants in a more precise and flexible way; and promoting the innovation of manufacturing and business models [8–10].

4.2.1 Intelligent manufacturing system architecture of a petrochemical plant

The infrastructure of petrochemical intelligent manufacturing is the petrochemical industry Internet platform, and the corresponding elements include data, models, and applications. These elements form a feedback closed-loop at different levels. The platform embodies the vertical integration of internal information in the petrochemical plant, the horizontal integration of the entire industry supply chain, and an end-to-end integration of engineering digitization. The architecture of the petrochemical intelligent manufacturing system is mainly divided into four levels: unified data platform, model platform, digital space, and application development platform (Fig. 3). The data platform has the collection, processing, and saving functions. Meanwhile, the model platform includes the establishment of mechanisms, numbers, and rules. The digital space mainly refers to digital twins based on factories, and the application development platform includes application developments, deployments, and operations.

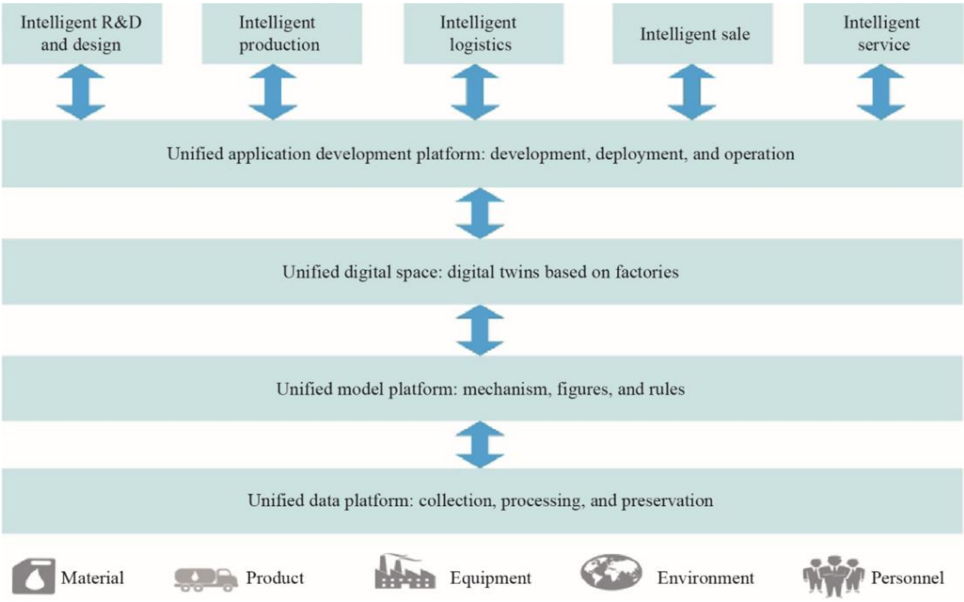

Fig. 3. Schematic of the architecture of an intelligent petrochemical manufacturing system.

4.2.2 Architecture of the intelligent manufacturing technology of a petrochemical plant

Combined with the characteristics of the petrochemical industry and the advantages of the new generation of information technology, the intelligent technology architecture of petrochemical plants mainly includes four aspects: factory computing, man–machine coordination intelligence, big data and knowledge automation, and an innovative manufacturing and management mode (Fig. 4) [11,12].

The intelligent application of petrochemical plants should focus on integrating the material, energy, and information flows and performing integrated optimization of the following six fields: research and development, supply chain management, production operation, operation decisions, industrial chain collaboration, and marketing and service.

5 Key tasks of the intelligentization of the process manufacturing industry

5.1 Building intelligent plants

In the aspect of intelligent plant design, a lifecycle-oriented engineering design should be created, an intelligent design platform should be constructed across the value chain, the design efficiency and quality be improved, and the digital delivery be realized. Hence, a good "gene" for an entire process simulation optimization, digital twin simulation, and factory high-performance operation can be formed.

In the aspect of intelligent production operation, the factory perception, online optimization control, and analytic decision-making ability should be enhanced through the vertical integration of internal enterprise information.

In the aspect of intelligent production management, intelligent production management should be improved through the optimization of intelligent equipment, quality, energy, data, human resources, and other aspects.

In the aspect of an intelligent supply chain, through the horizontal integration of the whole industry supply chain, the synergy of internal supply chain optimization and the whole industry supply chain coordination are achieved. Further, up-downstream enterprises and inter-industry collaborative operation are implemented to form a supply chain operation system that is visible, controllable, traceable, and integrated, which will support cost reduction, efficiency enhancement, supply and demand matching, and industrial upgrading.

In the aspect of intelligent service system, costs are reduced and customer satisfaction is enhanced through the

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establishment of intelligent product sales services and value-added services and integration of production, supply and marketing, and industrial chain services.

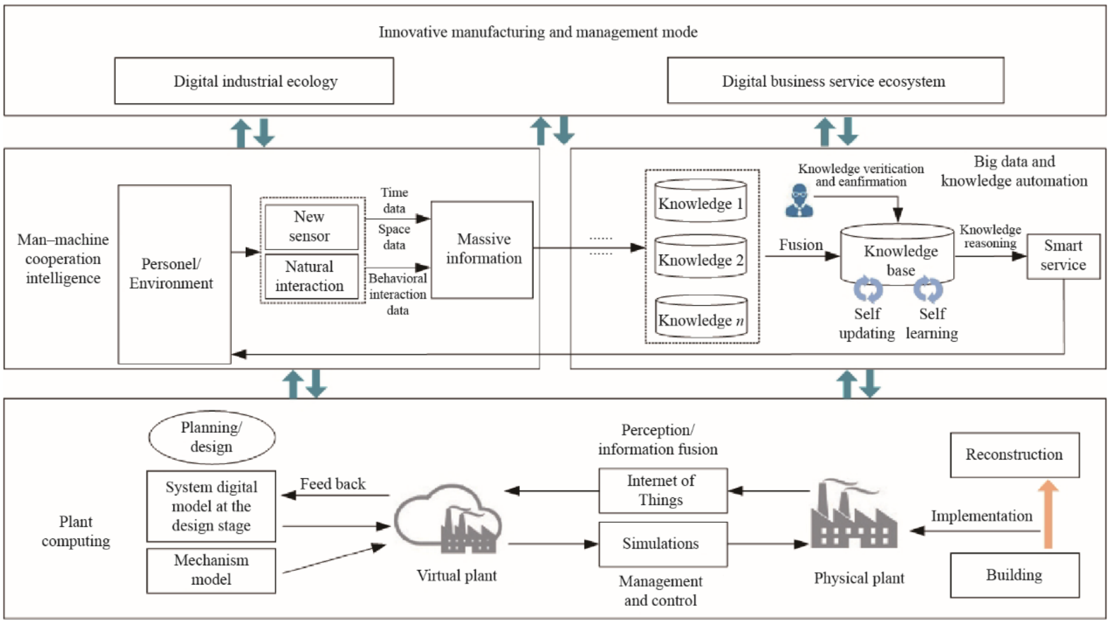

Fig. 4. Schematic of the intelligent technology framework for petrochemical plants.

5.2 Breakthroughs in key technologies and equipment

For intelligent steel plants, the key technologies and equipment that need to experience breakthroughs are as follows: collaborative optimization technology of the material, energy, and information flow networks; multi-layer, multi-scale intelligent modeling technology and solving method; whole process integrated scheduling and quality control technologies; information perception and digitalization technology and equipment under high-temperature, high-risk, and high-pollution conditions; industrial internet technology and equipment for iron and steel manufacturing processes; intelligent execution technology and equipment; and unmanned professional transport devices.

For petrochemical intelligent plants, the key technologies and equipment that require breakthroughs include the following: industrial IoT technology and equipment that meets the need of onsite petrochemical processes; big data modeling and intelligent analysis technology in the petrochemical industry; theory and technology of knowledge engineering in petrochemical enterprises; key technologies of virtual modeling and automatic control of petrochemical processes, those of intelligent instrumentation control, those of large unit health management and control, and those of intelligentization of equipment and pipelines; and technologies of process simulation and real-time online optimization.

5.3 Overcoming scientific engineering problems

For intelligent steel plants, the scientific engineering problems that should be solved include the following: the physical essence and constitutive characteristics of the iron and steel manufacturing process with a multi-objective optimization to achieve product manufacturing, energy conversion, and social waste disposal; and the integrated cyber–physic system, plant constitution, and management and control structure of steel manufacturing processes that cover the three elements of "flow," "process network," and "procedure."

For petrochemical intelligent plants, the scientific engineering problems that should be solved include the following: information automatic perception and intelligent analysis in the entire production and operation process; whole process control and optimization of "man–machine–object" coordination; intelligent monitoring and risk control of the entire lifecycle environmental footprint; intelligent prediction and early warning for production safety risks; and hybrid-augmented intelligence for man-in-the-loop [13].

5.4 Establishing a national standards system

The standards system structure of intelligent steel plants comprises two parts: "A: basic standards" and "B: key technology standards and industry application standards" (Fig. 5). "A: basic standards" includes five major categories: general, safety, reliability, testing, and evaluation. It is located at the bottom of the standards system structure of intelligent steel plants and forms the basis of the second part."B: key technology standards and industry application" is the projection of the manufacturing plane of the intelligent feature dimensions of the steel intelligent manufacturing reference model in the life-cycle and system-level dimensions.

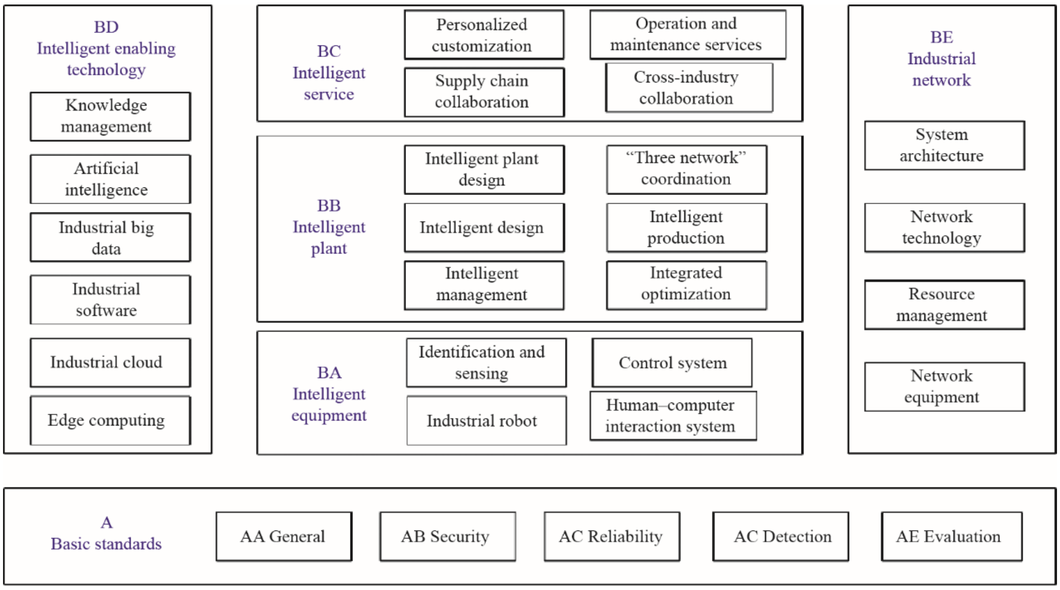

Fig. 5. Schematic of the standards system for intelligent steel plants.

The standards system structure of the intelligent petrochemical industry is composed of three parts: "A: basic and common standards," "B: key technology standards," and "C: subdivision industry application standards" (Fig. 6). It emphasizes the composition relationship of various parts of the standards system. "A: basic and common standards" includes five main categories: general, safety, reliability, testing, and evaluation. It is located at the bottom of the standards system structure of intelligent petrochemical plant and forms the basis of "B: key technology standards" and "C: industry application standards."

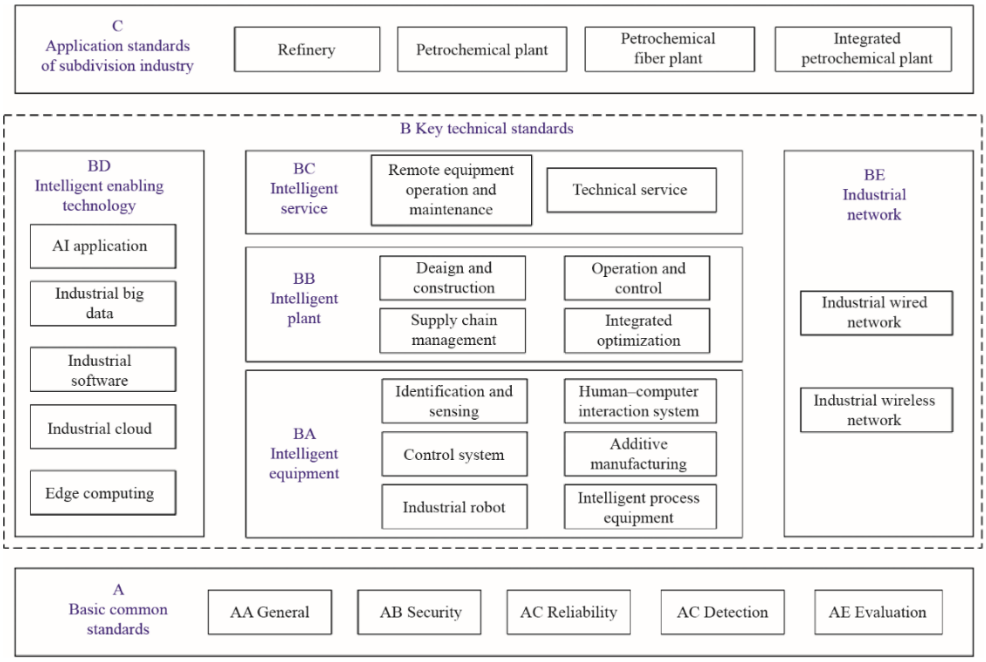

Fig. 6. Schematic of the structure of the intelligent manufacturing standards system in the petrochemical industry.

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s6 Paths of the intelligentization of the process manufacturing industry

6.1 Paths of the intelligentization for steel plants

For adopting a roadmap for the parallel implementation of digitalization, networking, and intelligence, implementing the model of "R&D–pilot demonstration –promotion and popularization" and clarifying the steps and breakthrough points of intelligent steel plants, the paths include the following:

(1) Through dynamic optimization of the engineering design and (or)"interface" technology optimization in the existing manufacturing process of steel plants, promote the collaborative optimization of material and energy flow networks, and set up a good physical foundation for the construction of intelligent steel plants. This makes the physical system architecture convenient for the introduction and penetration of information flow.

(2) Through a real-time perception of key informational elements (sequence parameters) in manufacturing processes, create an industrial Internet platform, fine-tune the information flow network structure and model of different levels (PCS, MES, EMS, or even ERP) and different processes (e.g., raw material field, ironmaking, steelmaking, rolling, and steel inventory systems), and move information between the physical and production control systems.

(3) Optimize the material, energy, and information flow networks; promote the integration of the three networks; and establish a collaborative optimized production control system for the intelligent production control, energy and environmental protection, and equipment operation and maintenance centers.

(4) Construct an intelligent management platform for the integration of "production, supply, and marketing" and business finance and provide the collaborative operation capability of the supply chain, value chain, and intelligent management and control center of the plant.

(5) Integrate the lifecycle product research and development, sales, and value-added services, expand the intelligent service chain, and realize the networking synchronization of the intelligent management/control and energy/environmental protection centers.

(6) Perform intelligent, dynamic, and precise designs and simulations, establish virtual plants based on process mechanism models and process operation rules, and realize the control, prediction, and continuous optimization of physical plants in the form of "digital twins.'

6.2 Paths of intelligentization of petrochemical plants

By 2025, based on the IoT technology, a real-time perception of all material elements, products, equipment, environment, and personnel in petrochemical plants will be realized, and a digitalized and networked petrochemical production environment will be formed. An industrial Internet platform for the petrochemical process will be developed, performing closed-loop optimizations including assets, processes, and businesses through data, models, and applications. Then, a highly automated petrochemical plant based on the cyber–physics system will be developed, realizing the control, prediction, and collaborative optimization of the physical plant through digital twins, performing digital transformation in various core business links, such as design, production, logistics, and service. Therefore, the response speed and risk response ability of enterprises to the market and energy efficiency will be improved, and the competitiveness of enterprises through data automatic flow will be strengthened.

By 2035, a wide application of the new generation of AI in petrochemical enterprises will be realized. The sales chains of upstream supplies and downstream supplies are able to provide efficient collaboration and resource optimization. Finally, intelligent and green manufacturing will be realized through self-perception, self-learning, self-determination, self-execution, and adaptation of petrochemical manufacturing systems.

7 Strategies and policy suggestions for the intelligentization of the process manufacturing industry

7.1 Strategies

(1) Start from basic research on the constitutive and intrinsic physical characteristics of process manufacturing industries, consider intelligent plants as the core, strengthen theoretical research, formulate intelligent standards and norms, and lay a solid foundation for the intelligentization of the process manufacturing industry.

(2) Fine-tune a top-level design; implement this design in the following manner: "overall planning–pilot demonstration–staged implementation–comprehensive promotion"; clarify the development ideas, development goals, key tasks, key technologies, and key technical and technological roadmaps of each stage; and reflect the

systematicness and orderliness of the work.

(3) Enhance the design plan of intelligent manufacturing plants in process manufacturing industries, deeply integrate the planning and engineering designs, solve the series of engineering problems that may be encountered, and develop an optimization design of intelligent plants in process manufacturing industries.

(4) In the fields of technology and equipment, promote the integration of "industry, university, institute, user" and strive to solve the technical problems encountered during the process of building intelligent plants in the process industry.

(5) Combine the actual situations of the development scale, technology level, and informatization level of the process manufacturing enterprises and carry out the intelligent plant construction in different categories.

(6) Improve the training mode for vocational education and professional talents, pay attention to sustainable development, and cultivate a group of professional and technical personnel to ensure the success of intelligent plants in process manufacturing industries.

7.2 Policy suggestions

(1) Establish a promotional mechanism for the intelligentization of process manufacturing industries, and promote the implementation of intelligent manufacturing strategies and the transformation and upgrading of process manufacturing industries.

(2) Aim at the theoretical and standards system and key technical bottlenecks that restrict the intelligentization of China's process manufacturing industry, and combine and adjust the establishment of intelligentization National Science and Technology Major Projects, National Key Research and Development Program, and technological innovation projects in the process manufacturing industry. Finally, list them in the national science and technology research projects in the 14th Five-Year, which aims to steadily increase the R&D resources input, optimize input structure, and substantially increase the proportion of basic research investment.

(3) Maintain the financial input from the government, take advantage of special funds for technological transformations to promote intelligent manufacturing, adopt a preferential tax policy, and increase the financial support for the development process of intelligent manufacturing.

(4) From the national level, increase the support for technological innovation in related fields, and set up key technology development projects for intelligent manufacturing in the process manufacturing industry. Further, focus on R&D in basic modeling, intelligent sensing, intelligent equipment, and industrial software to overcome the key technical bottlenecks of intelligent manufacturing processes and to gradually achieve independent safety and control.

(5) Establish a digital asset protection mechanism for intellectual property rights; introduce a digital asset licensing system; create a transparent digital asset usage environment; use information technology to encrypt, mark, trace, and monitor digital assets; and maintain legal constraints on violations.

(6) Deepen the intelligent international exchanges and cooperation in process manufacturing, encourage multinational corporations and foreign institutions to set up intelligent manufacturing R&D institutions and training centers in China, and construct demonstration intelligent plants for process manufacturing industries. Moreover, encourage domestic enterprises to participate in international mergers, acquisitions, and shares of foreign advanced R&D manufacturing enterprises, and actively promote exchanges and cooperation with the international intelligent manufacturing industry alliance and academic institutions to achieve a higher level of openness in the field of intelligent manufacturing.

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