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Development Strategy for an Intelligent Factory in Discrete Manufacturing

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Abstract: New-generation intelligent manufacturing, characterized by the marriage of next-generation artificial intelligence technology and the advanced manufacturing industry, is emerging as the core technology of the fourth industrial revolution. China's manufacturing industry, as a whole, is large, but not strong. The development of intelligent manufacturing can promote China's manufacturing industry by improving both quality and efficiency; ultimately, it is the main path for the transformation and upgradation of China's manufacturing industry. Intelligent production is a major component of intelligent manufacturing, while an intelligent factory is the carrier for intelligent production. This paper focuses on the development strategy for intelligent factories in discrete manufacturing. First, the concept of the intelligent factory is introduced, with a discussion of its basic structure, information system architecture, and the basic characteristics of discrete manufacturing. Then, the key directions for achieving a breakthrough and preparing the implementation plan for an intelligent factory are laid out. Finally, the following suggestions are provided for policy makers to develop an intelligent factory: ① actively support and guide the development of intelligent manufacturing through pilot and demonstration projects, and promote the formation of an ecological chain for intelligent manufacturing with regional advantages; ② encourage enterprises to build intelligent factories to gain technology-based competitive advantages and enhance economic benefits; ③ establish and improve the synergy mechanism for innovation; and ④ highlight the Made-in-China capabilities for core technologies, key equipment components, and industrial software.

Keywords: intelligent manufacturing; intelligent factory; discrete manufacturing

1 Introduction

The manufacturing industry has become the focus of the global economy; this has led to accelerated planning and structural adjustment in the industry around the world. China's manufacturing industry is large but not competitive; further, it is not very profitable and faces the challenge of high-end manufacturing returning to advanced countries, while low-end manufacturing moves to other developing countries. New-generation intelligent manufacturing, characterized by the marriage of next-generation artificial intelligence technology and advanced manufacturing industry, is emerging as the core technology of the fourth industrial revolution; this would have a revolutionary influence on industrial technology and the in-depth adjustment of division of labor [1]. Some of the strategic considerations for promoting development and achieving a structural economic change include retaining core intelligent manufacturing and promoting the industry by improving both quality and efficiency to further its transformation.

The development of intelligent manufacturing is the main

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path for the transformation and upgradation of China's manufacturing industry. The report on the 19th National Congress of the Communist Party of China suggests that China will work faster to become a manufacturer of quality and develop advanced manufacturing, promote further integration of the Internet, big data, and artificial intelligence with the real economy, and foster new growth areas and drivers of growth in medium- and high-end consumption, innovation-driven development, the green and low-carbon economy, the sharing economy, modern supply chains, and human capital services [2]. *China Manufacturing 2025* indicated that the marriage of new-generation information technology and manufacturing industry, as well as the promotion of intelligent manufacturing, is the key to improving both the quality and efficiency of the manufacturing industry [3].

New-generation intelligent manufacturing is a giant system that mainly consists of three functional subsystems: intelligent products, intelligent production, and intelligent services. It also includes the supporting systems of the industrial Internet and the intelligent manufacturing cloud [1]. Mittal et al. [3] discussed the characteristics and technology of an intelligent manufacturing system and concluded that intelligent production is a major component of intelligent manufacturing and an intelligent factory is the carrier for intelligent production.

There has been substantial exploration and progress in the intelligent factory field [4−9]. The basic characteristics of the intelligent factory are applying flexible automation, Internet of Things (IoT), artificial intelligence, and big data to the complete lifecycle of design, process planning, production, and factory operation. An intelligent factory will benefit in meeting customized requirements, production optimization, intelligent manufacturing, and management mode changes. An intelligent factory has two types of divisions of trade: discrete factory and process factory. Both pursue the same goals of optimizing production process and improving performance, function, quality, and efficiency of production. Manufacturing industry develops along customization, service orientation, artificial intelligence, cooperation, and ecological protection tracks. To achieve the goal of revitalizing the manufacturing industry, advanced industrial countries are developing a technological system based on new-generation network manufacturing and the intelligent factory; building innovative ecosystems; and trying to employ the leading technologies of the world.

China, the workshop of the world, has the largest manufacturing industry; this results in a strong demand for an intelligent factory. The construction of an intelligent factory is the key approach needed to form a flexible, customized, and intelligent production mode, besides driving the transformation of China's manufacturing industry. In this paper, we focus on the development strategy of intelligent factory in discrete manufacturing, which represents the hope for promoting the upgradation of China's manufacturing industry and making China's intelligent factories among the best of the world.

2 The connotation and basic structure of an intelligent factory

2.1 The connotation of an intelligent factory

Intelligent manufacturing is a combination of artificial intelligence and manufacturing technology. It is oriented to the whole lifecycle of products and based on the new generation of information technology, with its carrier being the manufacturing system. It has capabilities, such as a certain autonomy of perception, learning, analysis, forecasting, decision making, communication, and coordinated control, in its key links or processes. It can adapt to changes in the manufacturing environment dynamically, thereby achieving the objective optimization of quality, cost, delivery time, and so on.

Manufacturing systems, such as manufacturing equipment, manufacturing units, production lines, manufacturing workshops, manufacturing plants, and manufacturing ecosystem, range from the micro to the macro level. It consists of products, manufacturing resources, various process activities, as well as models of operation and management.

The intelligent factory is an intelligent manufacturing system at the plant level. It has an organic interconnection and ubiquitous perception of all the elements, such as equipment, materials, and environment, involved in product manufacturing within the factory through the IoT, along with digital and intelligent technologies, such as big data, cloud computing, and virtual manufacturing. The intelligent factory realizes functions, such as deep perception of the production process, intelligent decision making, and precise control; further, it achieves the objective of efficient, as well as high-quality management and control of the manufacturing process.

The intelligent factory is a production system based on a deep integration of information physics. Through the design and implementation of information and physical integration, the structure of the manufacturing system can be defined and the manufacturing process can be configured and verified. Driven by personalized production tasks and scenarios, the intelligent factory can reconstruct the production process, greatly reduce the organizational difficulty of the production system, and improve manufacturing efficiency and product quality. As the core technology for flexible, autonomous, and personalized production tasks, the intelligent factory will significantly improve the manufacturing level and competitiveness of enterprises.

2.2 The basic structure of intelligent factory

The basic structure of an intelligent factory has three dimensions (Fig. 1).

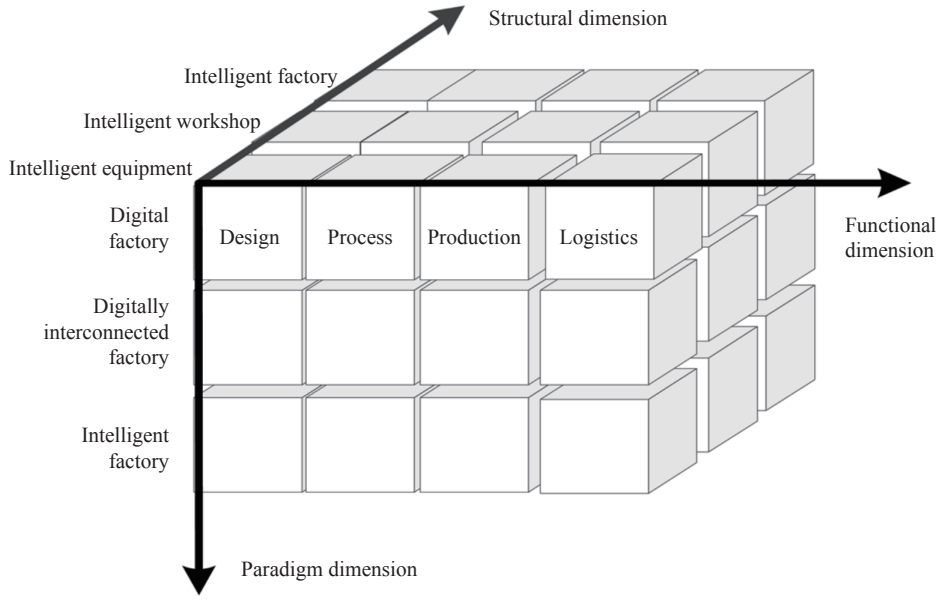

Fig. 1. Intelligent factory framework.

2.2.1 Functional dimension: product from virtual design to physical implementation

(1) Intelligent design

Through an intelligent analysis of big data, it obtains product requirements and design position accurately. Through the intelligent creation method, it designs the product concept. Through intelligent simulation and optimization strategy, it achieves high-performance product design and through the parallel collaborative strategy, it achieves effective feedback on design and manufacturing information. Intelligent design guarantees the creation of excellent products, as well as the rapid development and launching of products.

(2) Intelligent process

It includes virtual simulation and optimization of plants, rule-based process creation, process simulation analysis and optimization, process sensing, prediction, and control based on the cyber−physical system. Intelligent processes ensure consistent product quality and reduce manufacturing costs.

(3) Intelligent production

An intelligent production process, which can be realized by means of intelligent technology, requires the optimal allocation of production resources and production tasks; real-time optimization of logistics scheduling; refined management of production processes; and intelligent scientific management decisions. Intelligent manufacturing ensures optimal use of equipment; this increases responsiveness to the market and dilutes the depreciation of equipment related to each product. Intelligent production guarantees agile production and "just in case" inventory, ensuring the full flexibility of the production line and enabling companies to respond to market changes quickly and beat the competition.

(4) Intelligent logistics

Using IoT, one can not only actively identify materials, but also visualize and track the whole process. Through intelligent warehousing and logistics facilities, automatic material distribution and error prevention support can be realized. Through intelligent collaborative optimization technology, the precise synchronization of production logistics and planning can be realized. In addition, other processes, such as tool flow, are sometimes more complicated than material flow. For example, in a metal processing factory, one material may require hundreds of tools. Intelligent logistics guarantees "just in time" manufacturing, which reduces the capital consumption of work-in-process.

2.2.2 Paradigm dimension: evolution from digital factories, to digitally interconnected factories, and, finally, intelligent factories

Digital, networked, and intelligent technologies are the three key technologies for the innovation, transformation, and upgradation of manufacturing industries, which correspond to the evolution into digital factories, digitally interconnected factories, and intelligent factories. Digitization is the foundation for automated manufacturing and interconnection to achieve intelligent manufacturing. Networking is the integration of the original digital islands and provides a supporting environment for the implementation of intelligent and global optimization of the manufacturing system not just within the factory, but also the whole society. Intelligentization has been making full use of this environment, replacing human intervention with artificial intelligence in manufacturing, speeding up response, improving accuracy and scientificity, and ensuring the efficient, stable, and safe functioning of the manufacturing system.

(1) Digital factory

The digital factory is the embodiment of the integration of industrialization and informationization. It provides a comprehensive control solution for the entire production process of the manufacturing plant through integration, simulation, analysis, and control with the aid of informationization and digital technology. It is not limited to virtual factories; more importantly, it includes the integration of actual plants through product engineering, plant design and optimization, workshop equipment construction, and production action control (Fig. 2).

(2) Digitally interconnected factory

The digitally interconnected factory refers to the application of IoT to all aspects of the plant operation, thereby realizing the ubiquitous perception of people, machines, materials, methods, loops, measurements, besides the interconnection of everything within the factory. The scope of interconnection can even be extended to the supply chain and customer links. The interconnection of factories, on the one hand, can shorten the space-time distance, and lay the foundation for information sharing and collaborative work between the "human–human," "human−machine," and "machine−machine" pairs in the manufacturing process. On the other hand, the manufacturing process can obtain more comprehensive state data, which makes data-driven decision support and optimization possible.

(3) Intelligent factory

The deep integration of informatization and industrialization at the manufacturing plant level is the extension and development of digital factories, interconnected factories, and automated factories. By applying artificial intelligence technology to product design, process, production, and other processes, a certain intelligent features of manufacturing plants can be reflected in their key links or processes. These include the ability of perception, learning, analysis, prediction, decision making, communication, coordination, control of autonomy, and adapting to changes dynamically in the manufacturing environment; this leads to improvement in quality and efficiency, besides saving energy and reducing costs.

2.2.3 Structural dimension: evolution from intelligent manufacturing equipment and intelligent workshops to intelligent factories

Intelligence is reflected at different levels. It can be the intelligence of a single manufacturing equipment, the intelligence of the production line, the intelligence at the unit level, and the intelligence at the factory level.

(1) Intelligent manufacturing equipment

Manufacturing equipment, as the smallest unit of manufacturing, can play a distinguished role in the manufacturing process, self-analyze information related to equipment, processing status, workpiece materials, and environment, and make decisions autonomously according to product design requirements and real-time dynamic information. Its decision-making instructions are self-executing through the large-loop process of "perception−analysis−decision−execution and feedback." Performance and adaptability are improved continuously to achieve efficient, high-quality, safe, and reliable processing.

(2) Intelligent workshop (production line)

As shown in Fig. 3, the workshop (production line) consists of multiple intelligent equipment (production lines). In addition to basic processing/assembly activities, it also involves business activities, such as planning and dispatching, logistics and distribution, quality control, production tracking, and equipment maintenance. The intelligent production management and control capability is reflected in the closed-loop process of "optimization

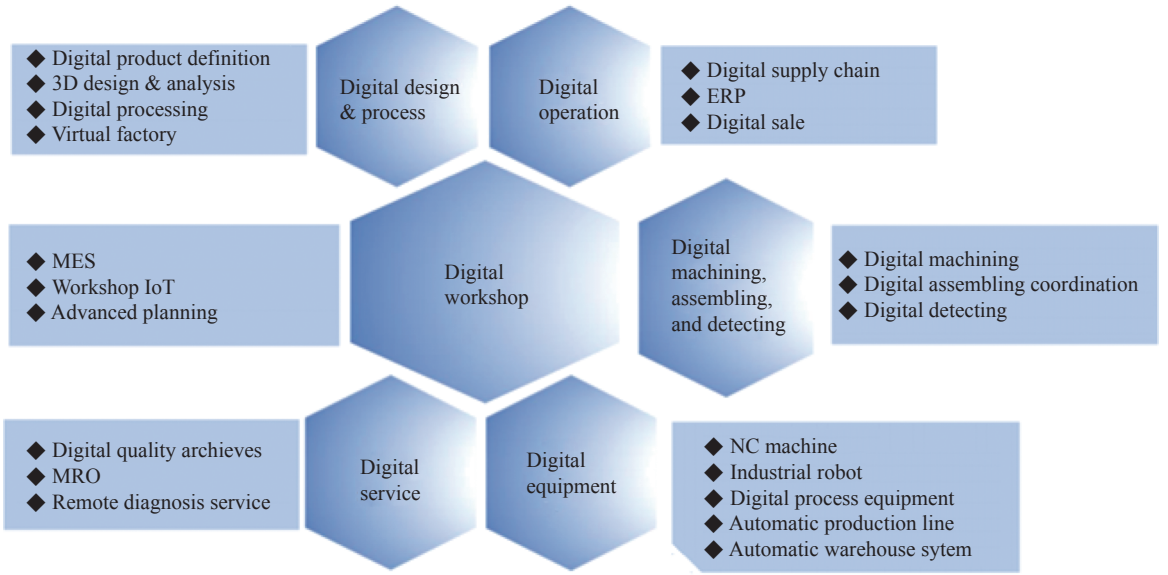

Fig. 2. Digital factory.

plan-intelligence-dynamic scheduling-coordination control" to improve the adaptability of production operations and the ability to quickly respond to abnormal changes.

(3) Intelligent factory

In addition to production activities, the manufacturing plant also includes business activities, such as product design and process and plant operations (Fig. 4). The intelligent factory is focused on the whole process of production and operation of the enterprise, and realizes rapid exchange, transmission, storage, processing, and seamless intelligent integration of all aspects, from product design to sales, and from equipment control to enterprise resource management.

2.3 Information system architecture of intelligent factory

With reference to IEC/ISO 62264 international standards, the information system architecture of the intelligent factory, as shown in Fig. 5, is constructed bottom to top as follows: the

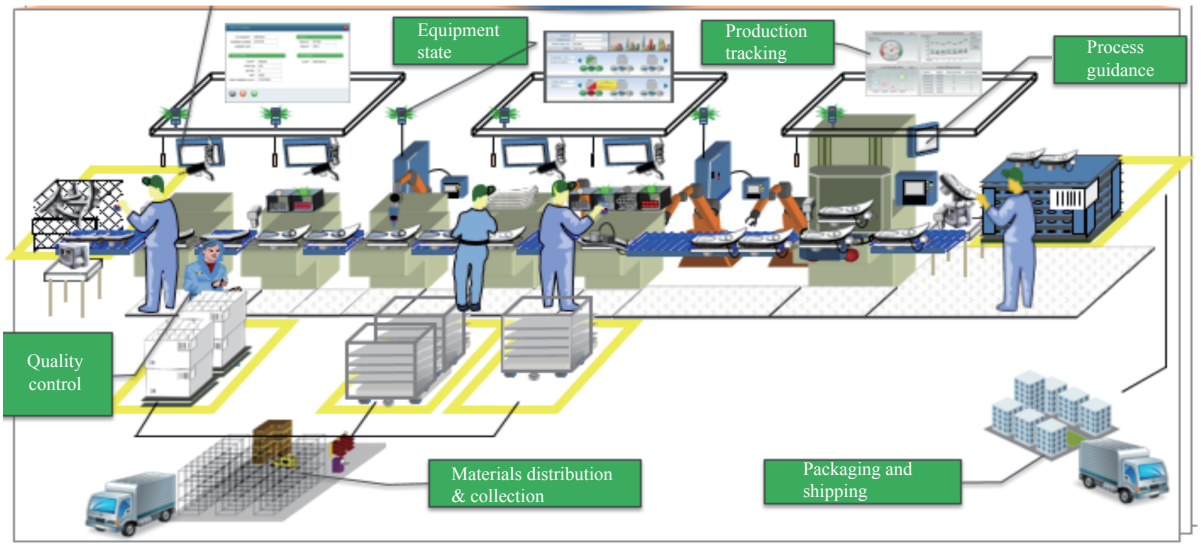

Fig. 3. Workshop activities.

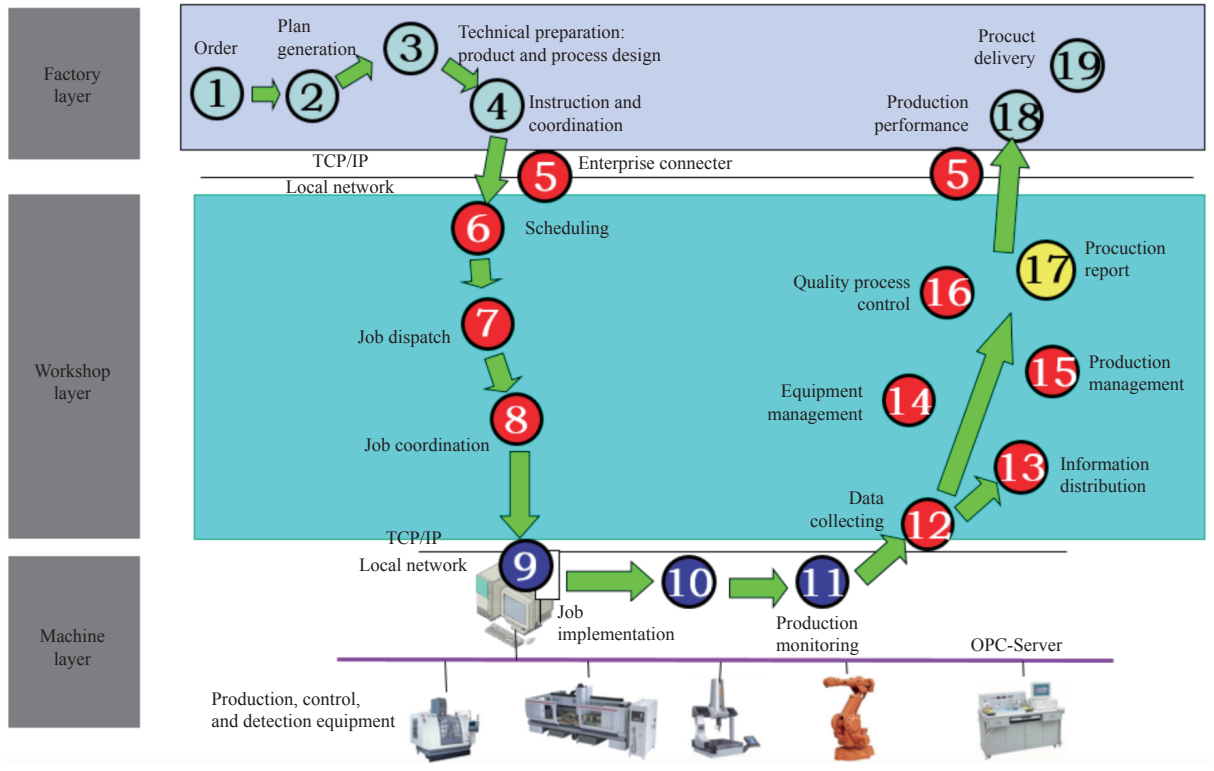

Fig. 4. General processes of manufacturing factories.

facility layer, the information acquisition and control layers, the manufacturing operation layer, the factory operation layer, and the decision analysis layer.

The decision analysis layer relies on the Internet and industrial Internet to decide the production mode and divide manufacturing tasks into those taking place inside the factory and outside. The facility layer is connected to the information acquisition and control layer through the industrial network bus; the remaining layers are connected through the LAN.

2.4 Basic features of intelligent factory

The features of the intelligent factory, as shown in Fig. 6, can be described from three perspectives:

From the construction goals and vision perspective, intelligent factories have the following five features: agility; high productivity; high quality output; sustainability; and comfortable and humanized ambience.

From a technical point of view, intelligent factories have the following five features: comprehensive digitalization; manufacturing flexibility; factory interconnection; high human-machine synergy; and process intelligence (intelligent control).

From an integration perspective, intelligent factories have the following as their three main features: end-to-end integration of product lifecycles; vertical integration of factory structures; and horizontal integration of supply chains; these are consistent with the three integration concepts of "Industry 4.0."

3 The key breakthrough directions and implementation approaches for an intelligent factory

3.1 The key breakthrough directions and technologies

3.1.1 Infrastructure of an intelligent factory—Intelligent manufacturing equipment and Industrial big data technology

Research on the basic levels—manufacturing equipment intelligentization, acquisition and conversion of multi-source heterogeneous data, safe and reliable transfer and efficient computation of big data, big data analysis driven by manufacturing business, and so on—of an intelligent factory, needs to be expanded in the following areas: ① Information collection in the manufacturing process and intelligentization of manufacturing equipment;② Intelligent factory information physical system; ③ Manufacturing big data standards and information security; ④Intelligent factory big data analysis and application platform;⑤ Intelligent cloud data organization and real-time operation.

3.1.2 Manufacturing resource modeling and organization optimization

For dynamic and volatile markets, we need to optimize the utilization of social resources and internal resources in company, and model the manufacturing resource, including: ① Factory resource modeling(development capability, manufacturing capa-

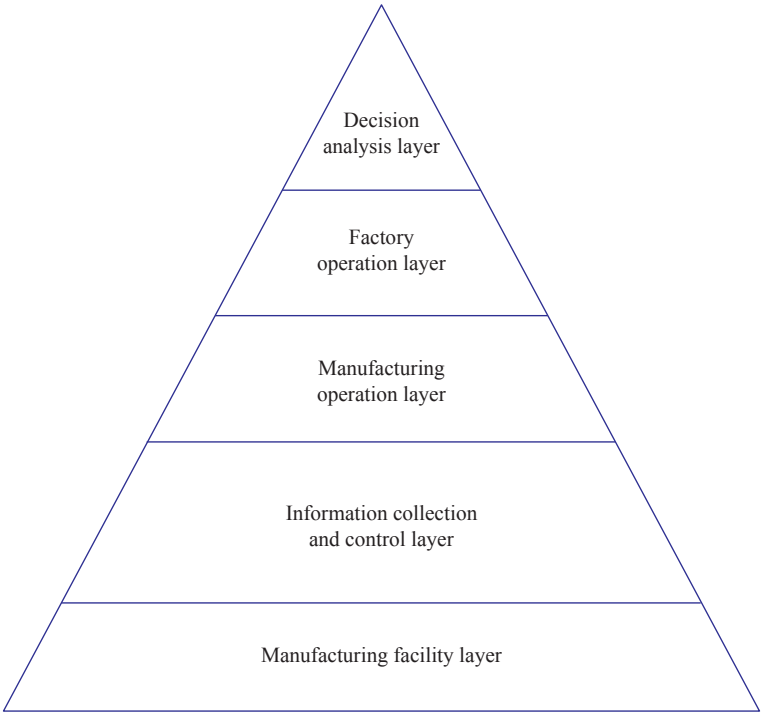

Fig. 5. Information system framework of manufacturing factories.

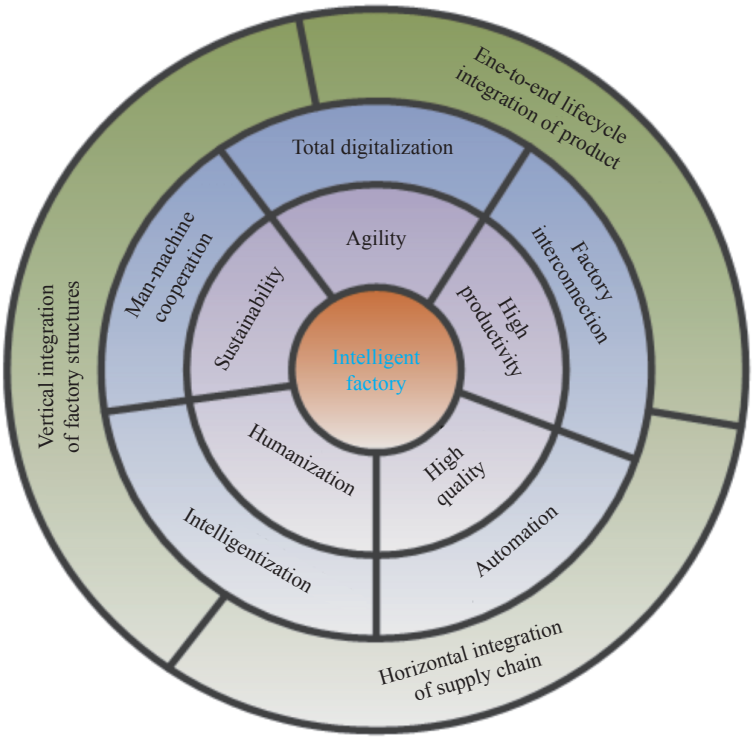

Fig. 6. Features of an intelligent factory.

bility, management); ②Manufacturing task description modeling (quality, cost, and delivery date); ③ Flexible design and dynamic management of manufacturing resources; ④ Modeling based on delivery data, manufacturing resource and capital chain.

3.1.3 Intelligent factory enabling technology

The core software and hardware of the intelligent factory are important enabling technology for intelligent manufacturing, including: ① Design and development that meet the personalized requirement (including additive manufacturing technology); ② Task-oriented internet construction;③ VR/AR system for intelligent factory applications;④ Manufacturing equipment intelligent monitoring and security technology and system; ⑤ Manufacturing engineering intelligent control and software, for example, cutting process and tool optimization control; ⑥ Production line management and control system; ⑦ Benefit-constrained, intelligent manufacturing task decision-making software; ⑧ Intelligent logistics technology and equipment.

3.1.4 Technical verification and demonstration area planning

Provide demonstration and verification technology, besides promoting development and application, including: ① Technical verification of various enabling technologies; ② Application of new-generation AI technology (big data intelligence, human–machine mixture intelligence, group intelligence, cross-media intelligence, and autonomous intelligence) in the intelligent factory;③ Cultivate intelligent technology service industries; ④ Regional demonstration by choosing the following representative demonstration areas: Pearl River Delta, Yangtze River Delta, Beijing–Tianjin–Hebei–Shandong, Greater Xi'an (Belt and Road and Aerospace); ⑤ Field demonstration: aerospace, CNC machine tools and basic manufacturing equipment, electronic information, engineering machinery, rail transit, household electrical appliance, and so on ⑥ 3D printing production line demonstration. 3D printing has been disruptive and will become an important production mode in the 21st century.

3.2 Implementation approaches

Along with the specific conditions and characteristics of the Chinese factory, it is necessary to consider the following four aspects of the implementation plan of the intelligent factory, and at the same time, highlight the level of development in, and the specific content of, different stages.

(1) Digital transformation: Realize the lifecycle digitalization of products based on end-to-end integration of product lifecycle management, and expand industrial data-aware acquisition, preliminary data mining, and data visualization.

(2) Network upgrade: Realize vertical integration of factory planning, management, operation, execution, and so on, driven by the industrial Internet and industrial big data, and lay the foundation for intelligent factories with intelligent equipment.

(3) Intelligentization upgrade: Establish a cyber−physical production system (CPPS), and apply the new generation of artificial intelligence to achieve the horizontal integration of factories based on the construction and application of products,

manufacturing equipment, processes, supply chain (logistics process) and other aspects, and different levels of digital hygiene.

(4) Intelligentization reform: The large number of manufacturing enterprises, who have operated effectively, can adopt sensor technology, big data technology, and intelligent software technology to transform their manufacturing equipment and production lines, thereby achieving intelligent transformation, and gaining huge profits with smaller investment.

4 Suggestions for developing an intelligent factory

Actively support and guide the development of intelligent manufacturing through pilot and demonstration projects. On this foundation, implement intelligent reformation of manufacturing equipment and enterprise. Finally, promote the formation of an ecological chain for intelligent manufacturing with regional advantages.

Encourage enterprises to build intelligent factories based on their existing situation and simultaneously fill the missing gaps in "industry 2.0" and "industry 3.0," besides focusing and preparing for the advanced technology of intelligent manufacturing offered by "industry 4.0." Consequently, build an organic link between the advanced and the conventional to achieve different levels of development in the functional, structural, and paradigm dimensions. Ultimately, construct technology-based competitive advantages and enhance economic benefit.

Establish and improve the synergy mechanism for innovation. In the plan for achieving synergy between science and technology, standard and basic research should be accorded priority; further, the industrialization of generic technology based on innovative ideas and invention patents, should be valued. In the synergy between industry, academia, and research, enterprises should be expected to invest in research, apply theory, and integrate innovations. In the synergy between finance, science, and industry, the funding environment of the manufacturing industry should be improved. Eventually, to create talent synergy, scientific discipline evaluation criteria should be created to guide innovation and engineering capability.

Highlight the Made-in-China capabilities for core technologies, key equipment components, and industrial software. It is essential to avoid the possibility of China becoming the dumping ground for high-end equipment and industry software from developed countries, and its manufacturing industry lacking core technology.

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