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# Three Basic Paradigms of Intelligent Manufacturing: Digital Manufacturing, "Internet Plus" Manufacturing, and New-Generation Intelligent Manufacturing

**Zang Jiyuan [1,2], Wang Baicun [1,2], Meng Liu [1,2], Zhou Yuan [2]**

1. The CAE Center for Strategic Studies, Beijing 100088, China;
2. School of Public Policy & Management, Tsinghua University, Beijing 100084, China

**Abstract:** This paper briefly describes the significance of studying the paradigms of intelligent manufacturing and introduces the connotation and development process of intelligent manufacturing. By analyzing the characteristics of relevant models, three basic paradigms of intelligent manufacturing are identified: digital manufacturing, smart manufacturing (i.e., "Internet plus" manufacturing), and digital-networked intelligent manufacturing (i.e., new-generation intelligent manufacturing). The meanings and characteristics of the three basic paradigms are expounded. China should begin with digital manufacturing to consolidate the foundation for intelligent manufacturing development. Then, China should focus on developing "Internet plus" manufacturing in parallel with the other two paradigms. The new-generation intelligent manufacturing will fundamentally propel the fourth industrial revolution and offer a historic opportunity for China's manufacturing to realize "lane-changing and overtaking" and achieve leapfrog development.
**Keywords:** basic paradigms; digital manufacturing; "Internet plus" manufacturing; new-generation intelligent manufacturing

## 1 Research background

Currently, the global manufacturing industry is changing, and the manufacturing industry has become the focus of global competition once again. In the 40 years since the "reform and opening up" (Chinese economic reform), China's manufacturing industry has developed rapidly, achieving accomplishments that have attracted worldwide attention. China has constructed an independent and complete manufacturing system of the largest scale in the world with all necessary industrial capabilities. However, despite the size, the strength of the system is still lacking. Furthermore, the industrial level remains at the low-to-medium end. To respond to the backflow influence caused by high-end manufacturing in developed countries and to compete with emerging markets enjoying the advantages of low costs, China's manufacturing industry should not develop by simply copying the extensive sequential growth model. It should instead promote high-quality development under the condition of intelligent manufacturing [1].

New-generation information technology (i.e., new-generation artificial intelligence (AI)) has developed rapidly. Its integration with manufacturing has also hastened, creating a trend that brings new opportunities to the transformation and upgrading of the global manufacturing industry. Various entities, such as the government, industry, academic institutions, research groups, and financial sectors, in China have quickly grasped the opportunities to guide the push for intelligent manufacturing. Intelligent manufacturing is key to the innovative development of China's manufacturing industry, the main path for the transformation and upgrading of the industry, and a primary direction enabling China

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**Corresponding author:** Zhou Yuan, Tsinghua University, Associate Professor. Major research field is public policy. E-mail: zhou_yuan@mail.tsinghua.edu.cn
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to become a manufacturing powerhouse [2].

Corporations are the main bodies of intelligent manufacturing, and improvements in quality and revenue are the objectives when implementing intelligent manufacturing. In recent years, during the promotion of intelligent manufacturing, some corporations have had the problem of implementing intelligent manufacturing blindly, i.e., doing it for the sake of doing it, and thus deviating from valid objectives. This shows that many corporations still face confusion and misunderstanding with regard to rational development directions and destination options associated with intelligent manufacturing. Therefore, it is paramount to clarify the definition and connotation of intelligent manufacturing and to summarize its basic paradigms. Only then can we effectively push forward the transformation and upgrading of Chinese manufacturing companies.

## 2 Connotation, development process, and basic paradigms of intelligent manufacturing

### 2.1 Connotation of intelligent manufacturing

In the broader definition, intelligent manufacturing is the deep integration between new-generation information technology and advanced manufacturing. It is embedded in the full lifecycle of the product, manufacturing, and service and the optimal integration of the corresponding systems to realize the digitalization, networking, and intelligence of manufacturing. Furthermore, it continues to improve the company's product quality, efficiency, and service level, and it promotes manufacturing industrial innovation with green, coordinated, open, and shared development [1].

### 2.2 Development process of intelligent manufacturing

The concept and technological development of intelligent manufacturing has progressed for decades. Japan proposed the intelligent manufacturing system (IMS) in the 1980s, then the United States proposed the cyber physical system (CPS). Germany proposed Industry 4.0, and China proposed "China Manufacturing 2025." Thus, intelligent manufacturing has had an extensive influence over the industrial transformation strategies of major countries worldwide. With decades of development, endless numbers of intelligent manufacturing-related paradigms have emerged, such as lean production, flexible manufacturing, concurrent engineering, agile manufacturing, digital manufacturing, computer-integrated manufacturing, networked manufacturing, cloud manufacturing, and intelligent manufacturing. Lean production originated with Toyota Motor Corporation of Japan in the 1950s and is still widely used in manufacturing. Its goal is to produce the required products as needed, when needed, and it is composed of just-in-time production, total quality management, total productive maintenance, and human resource management. Lean production reflects the idea of continuous improvement and is one of the foundations of intelligent manufacturing [3]. Flexible manufacturing entered the practical stage in the early 1980s. It is an automated manufacturing system comprising numerical control equipment, material storage, transportation devices, and digital control systems. It can be quickly adjusted to changes in manufacturing tasks and production environments. It is suitable for various types of small- and medium-sized productions. The system has the flexibility, agility, and precision of a full production and supply chain. Parallel engineering uses digital tools to consider the product lifecycle in the product concept stage, emphasizing the parallel crossover progression of product design, process design, production technology preparation, procurement, production, and other stages and allowing firms to start work as early as possible in an orderly manner. Agile manufacturing was born in the 1990s. With the development of information technology, enterprises used information tools to quickly and effectively respond to users and market demands by rapidly configuring resources, such as technology, management, and human resources. In 1986, China began to study computer-integrated manufacturing. It combines traditional manufacturing technology with modern information technology, management, automation, and system engineering. With the help of computers, the organic integration and optimized operation of people, management, and technology at all stages of the full product lifecycle are realized [4]. At the beginning of the 21st century, networked manufacturing was born. It combined advanced network technology, manufacturing technology, and other related technologies. It is a new model that improves a company's rapid response to the market and competitiveness [5]. In recent years, to solve more complex manufacturing problems and to conduct larger-scale collaborative manufacturing, a new service-oriented model of networked manufacturing (i.e., cloud manufacturing) has rapidly developed [6]. Intelligent manufacturing is the continuous development and in-depth application of new-generation information technology, sensing technology, control technology, and new-generation AI in manufacturing. Product manufacturing and services thus acquire the abilities of self-adaptation, self-learning, and self-decision, creating a future-oriented manufacturing paradigm [7].

These paradigms include both the basis of intelligent manufacturing and the different dimensions of value realization, technical-path upgrading, and organization methodology. They reflect different perspectives and characteristics of digitalization, networking, and intelligence of manufacturing, and have played an active role in the transformation of the manufacturing industry from automation towards intelligentization. However, many intelligent manufacturing paradigms pose difficulties for corporations in choosing technology paths or promoting intelligent upgrading. Faced with so many new technologies, new ideas, and new models of intelligent manufacturing, it is urgent to summarize the basic paradigms, to develop a consensus on intelligent manufacturing for Chinese enterprises, and to better

serve the intelligent transformation and optimization of China's manufacturing industry.

### 2.3 Three basic paradigms of intelligent manufacturing

Intelligent manufacturing is the product of the deep integration of manufacturing and information technologies. The birth and evolution of relevant paradigms are closely related to the characteristics of digitalization, networking, and intelligence. These paradigms have had digital characteristics since their birth, whereas computer-integrated manufacturing, networked manufacturing, cloud manufacturing, and intelligent manufacturing, etc., have had characteristics of networking. Intelligent manufacturing that will incorporate new-generation AI in the future will have characteristics of intelligence, as shown in Table 1.

According to the basic technical characteristics of digitalization, networking, and intelligence, intelligent manufacturing can be summarized by three basic paradigms: digital manufacturing (i.e., first-generation intelligent manufacturing), smart manufacturing (i.e., "Internet plus" or the second-generation intelligent manufacturing), and digital-networked intelligent manufacturing (i.e., new-generation intelligent manufacturing) (Fig. 1).

China's manufacturing industry has the most comprehensive independent industrial system in the world with all necessary industrial capabilities. It includes discrete manufacturing, such as those for mechanical and electrical products, as well as process manufacturing, such as petrochemical, metallurgical, building materials, and electric power. The intelligent manufacturing discussed here includes digitalization, networking, and intelligence for discrete manufacturing and process manufacturing.

## 3 Digital manufacturing

The first generation of intelligent manufacturing is digital manufacturing, which is the first paradigm. In the late 1980s, the idea of intelligent manufacturing was first proposed. At that time, digital manufacturing was the basis of the two latter intelligent manufacturing paradigms.

Since the second half of the 20th century, owing to the strong demand for technological advancement in the manufacturing industry, digital manufacturing has led to the third industrial revolution. Represented by computer numerical control (CNC), digital technology has been widely used in manufacturing industries to promote the manufacturing revolution. Digital manufacturing can quickly produce products that satisfy user requirements via the digital description, integration, analysis, and decision sup-

**Table 1.** Basic technical characteristics of intelligent manufacturing-related paradigms.

| Digitalization | Networking | Intelligence |
|---|---|---|
| Intelligent manufacturing | Intelligent manufacturing | Intelligent manufacturing |
| Cloud manufacturing | Cloud manufacturing | |
| Networked manufacturing | Networked manufacturing | |
| Computer-integrated manufacturing | Computer-integrated manufacturing | |
| Digital manufacturing | | |
| Agile manufacturing | | |
| Concurrent engineering | | |
| Flexible manufacturing | | |
| Lean production | | |

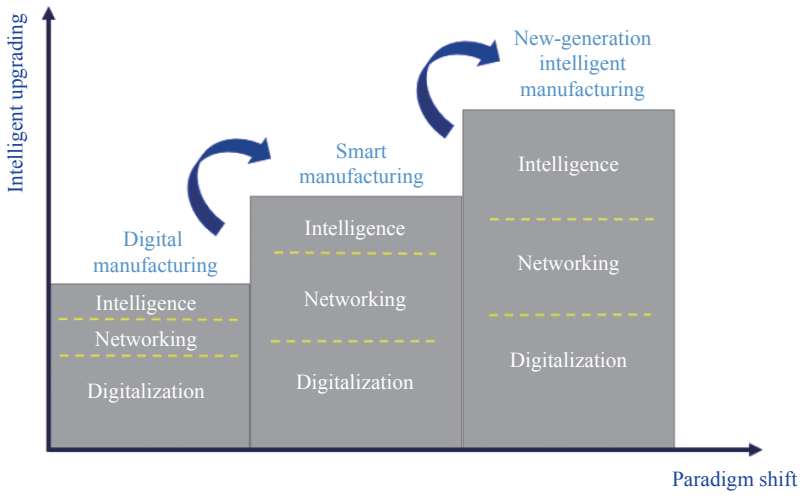


**Fig. 1.** Evolution of the basic paradigms of intelligent manufacturing.

port of product information, process information, and resource information in the context of the integration of manufacturing and digital technologies. Digital manufacturing focuses on improving corporate internal competitiveness, improving product design, improving manufacturing quality, increasing labor productivity, shortening new product development cycles, reducing costs, and improving energy efficiency.

The main features of digital manufacturing are as follows. First, with regard to products, digital technology has been widely used to form a "digital generation" of innovative products, such as CNC machine tools. Second, digital design, modeling, and simulation methods, such as computer-aided engineering, computer-aided process planning, and computer-aided manufacturing in computer-aided design or engineering design are widely used; digital equipment—such as CNC machine tools—is also widely used; the information management system, which uses manufacturing resource planning, enterprise resource planning, and product data management are used to manage various types of information in the manufacturing process and real-time information on the production site, hence enhancing the efficiency and quality at each production stage. Third, the integration and optimization of all aspects of the production process has resulted in solutions represented by the computer integrated manufacturing system. At this stage, early network technologies represented by fieldbus and early AI technologies represented by expert systems were applied to manufacturing.

In the 1980s, Chinese enterprises began to understand and apply digital manufacturing. After decades of development, many enterprises have digitized the entire processes of design, manufacturing, management, etc., and have promoted digital manufacturing equipment and numerical control systems. The achievements of enterprise informatization are remarkable. In recent years, Guangdong, Jiangsu, Zhejiang, and other locations have vigorously promoted "machine substitution" and "digital transformation," establishing several digital production lines, digital workshops, and digital factories. Many enterprises have completed digital upgrades. China's digital manufacturing has entered the development stage, transitioning from exploration and demonstration to promotion and popularization. It is necessary to realize that the number of enterprises that have truly completed the transformation to digital manufacturing in China is still small relative to China's large enterprise base, especially with regard to small- and medium-sized enterprises. Therefore, China's intelligent manufacturing development should adhere to the principle of seeking truth from facts and start from a digital "make-up lesson" to strengthen the foundation of intelligent manufacturing development. However, it must also recognize that western developed countries are promoting networked manufacturing on the basis of the widely applied digital manufacturing. However, China does not have to follow this sequential development path. We should therefore promote digital manufacturing and smart manufacturing in parallel, while helping enterprises to complete digital manufacturing "make-up lessons" while achieving smart manufacturing upgrading.

Digital manufacturing is the foundation of intelligent manufacturing, and its connotation is constantly changing via the three basic paradigms and development processes of intelligent manufacturing. The digital manufacturing defined here is the first basic paradigm, which is a relatively narrow definition. There are also several generalized definitions and theories about digital manufacturing in the literature.

## 4 "Internet plus" manufacturing (smart manufacturing)

The second generation of intelligent manufacturing is smart manufacturing, which is the second paradigm of intelligent manufacturing. In essence, it is "Internet plus" manufacturing. It achieves networking on the basis of digital manufacturing, and it applies the technology of the industrial Internet and industrial cloud to achieve connection and integration, while also having a certain degree of intelligence.

At the end of the 20th century, Internet technology developed rapidly and became widely popularized and applied. "Internet plus" continued to promote the integrated development of manufacturing and the Internet. The close combination of manufacturing technology with digital and network technologies reshaped the value chain of the manufacturing industry and promoted the paradigm shift from digital manufacturing to smart manufacturing.

"Internet plus" manufacturing applies in-depth advanced communication technology and network technology based on digital manufacturing, using networks to connect people, processes, data, and things and connecting "information islands" within and between enterprises. It achieves optimization of the industrial chain, providing the products and services required by the market quickly, with high quality and low cost, via collaboration within and between enterprises and via the sharing and integration of various social resources. The integration of advanced manufacturing and smart technologies enables enterprises to adapt to market changes more quickly and better collect user evaluation information on product use and product quality, thus achieving a higher level of flexibility in manufacturing and management informatization.

"Internet plus" manufacturing is significantly different from the previous manufacturing model, with regard to the products, manufacturing, and services. It has realized connectivity and information feedback of the manufacturing system, and its main characteristics are—with regard to products—digital and network technologies. Some products can connect and interact via the network, thus becoming a network terminal. Second, with regard to manufacturing, the connection and optimization of the supply chain and value chain within and between enterprises are realized, and the data flow and information flow of the entire manufacturing system are allowed. Via the design and manufac-

turing platform, enterprises can achieve optimal configurations of manufacturing resources and conduct business-process coordination, data coordination, and model collaboration with other enterprises to achieve collaborative design and manufacturing. The production process is flexible, enabling the mixed production of small batches and multiple varieties. Third, with regard to services, enterprises and users can connect and interact through the network platform. The enterprises can grasp the individual needs of the users, and users can participate in the product life-cycle activities, thus extending the industry chain to provide services, such as product health protection. New modes and new business types have emerged, including large-scale individual customized production, remote operation, maintenance services, full-lifecycle quality tracing services, and network collaborative manufacturing centered on supply-chain optimization. Large-scale customized production has gradually become a common model for the development of consumer goods manufacturing, and the remote operation and maintenance service model has been widely used in the construction-machinery industry. The production of enterprises began to transform from product-centered to user-centered, and the corporate form gradually shifted from production-oriented enterprises to production-service-oriented enterprises.

Since the beginning of the 21st century, major countries in the world have accelerated the development of intelligent manufacturing. Germany's Industry 4.0 uses CPS as the core, digitizing and integrating products, manufacturing, and services to realize interconnection and integration within and between enterprises. The US's Industrial Internet proposes to deeply integrate global industrial systems with advanced computing, analysis, sensing technology, and the Internet to restructure global industries and stimulate productivity. Industry 4.0 and the Industrial Internet have completely elaborated and proposed the smart manufacturing paradigm and the technical route to be realized.

China's industry has seized the strategic opportunity of Internet development and has vigorously promoted "Internet plus" manufacturing. Whereas a number of enterprises have undergone digital transformation, they have gradually cultivated intra-enterprise and inter-enterprise interconnections and have formed typical pilot demonstration projects. For example, the Haier Group established an interconnected factory centered on an intelligent manufacturing execution system (iMES) to respond to global user needs simultaneously in real time and to deliver intelligent, personalized solutions quickly. Foshan Weishang Furniture Manufacturing Co., Ltd. built a "new home network," i.e., an interactive open design platform to fully tap the individual needs of consumers, achieving consumption-driven production, and established a "large-scale furniture design customization production system" to effectively solve the contradiction between individualized customization and standardized mass production. Xi'an Aircraft Industry (Group) Co., Ltd. built the Aircraft Collaborative Development and Manufacturing Cloud Platform (DCEaaS) to achieve collaborative development, manufacturing services, resource dynamic analysis, and elastic configuration involving 10 research institutes and more than 60 suppliers.

In the next stage, China's focus on promoting intelligent manufacturing involves promoting and applying large-scale "Internet plus" manufacturing (i.e., second-generation intelligent manufacturing).

## 5 New-generation intelligent manufacturing (digital-networked intelligent manufacturing)

New-generation intelligent manufacturing (i.e., digital-networked intelligent manufacturing) is the third basic paradigm of intelligent manufacturing, corresponding to intelligent manufacturing.

Since the 21st century, new-generation information technologies, such as mobile Internet, supercomputing, big data, cloud computing, and Internet of Things, have developed rapidly, and they have concentrated on the breakthrough of AI technologies. The deep integration of AI and advanced manufacturing technology has formed a new generation of intelligent manufacturing: digital-networked intelligent manufacturing, which has become the core driving force of the next industrial revolution. The main feature of the new-generation intelligent manufacturing is that the manufacturing system can cognitively learn. Through the application of technologies, such as deep learning, enhanced learning, and migration learning, the efficiency of knowledge generation, acquisition, application, and inheritance in the manufacturing field of the new-generation intelligent manufacturing will undergo revolutionary changes, significantly improving the innovation and serviceability. With the transformation of manufacturing knowledge and production methods, a new generation of intelligent manufacturing has formed a new manufacturing paradigm.

New-generation intelligent manufacturing will bring revolutionary changes to the manufacturing industry. It is intelligent manufacturing in the true sense, and it will fundamentally lead and promote the fourth industrial revolution, bringing historic opportunities for China's manufacturing industry to achieve "lane-changing and overtaking," as well as leapfrog development. If smart manufacturing can be the beginning of a new round of the industrial revolution, the breakthrough and widespread application of new-generation intelligent manufacturing will push us toward its climax.

## 6 Conclusion

This paper analyzed the connotation and characteristics of the three basic paradigms of intelligent manufacturing. Accordingly, we summarized the two characteristics of intelligent manufacturing development [8]: continuity and integration.

The three basic paradigms of intelligent manufacturing possess continuity with regard to time and the goal. Digital manufacturing, “Internet plus” manufacturing, and new-generation intelligent manufacturing occurred sequentially, with the same focus on improving manufacturing efficiency and quality, reflecting the interim characteristics of the integration and development of new-generation information and advanced manufacturing technologies [1].

Digital manufacturing, “Internet plus” manufacturing, and new-generation intelligent manufacturing paradigms are not separate but intertwined and iteratively upgraded. For example, in the digital manufacturing paradigm, information and communication technologies, as well as the first-generation AI technologies, have already been applied. When digital technology and network technology are fully developed, each basic paradigm of intelligent manufacturing can integrate various advanced technologies as needed in its development, reflecting the integration characteristics of intelligent manufacturing development.

Combining the knowledge of China’s national conditions and the understanding of the continuity and integration of intelligent manufacturing, China’s promotion of intelligent manufacturing should adopt the technical route of “parallel promotion and integrated development” of three basic paradigms to achieve intelligent upgrading and further the development of the manufacturing industry.

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